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Tese de Doutorado

# EFEITO DA CARGA E DA IDADE NA MECÂNICA DA CORRIDA DE VELOCIDADE

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Porto Alegre, dezembro de 2016

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Tese de Doutorado apresentada ao Programa de Pós-Graduação em Ciências do Movimento Humano da Universidade Federal do Rio Grande do Sul, como requisito parcial para obtenção do título de Doutor em Ciências do Movimento Humano.

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*“Ensina-me a encontrar Tua presença no altar da minha paz constante e na alegria que jorra da meditação profunda.”*

***(Paramahansa Yogananda)***

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# RESUMO

Esta tese busca avaliar dois efeitos que podem influenciar os principais parâmetros de um modelo teórico que caracteriza a fase de aceleração da corrida de velocidade: o efeito da carga e o efeito da idade. Os parâmetros do modelo incluem variáveis que caracterizam as relações força-velocidade e potência-velocidade, assim como a capacidade do atleta de direcionar a aplicação de força contra o solo, horizontalmente (efetividade mecânica). O objetivo do primeiro artigo foi comparar o efeito de diferentes cargas colocadas em um trenó com a corrida sem carga, sobre a efetividade e sobre parâmetros determinantes das relações força-velocidade e potência-velocidade, durante toda a fase de aceleração, em atletas velocistas. Este estudo mostrou que a efetividade mecânica aumenta com o aumento da carga utilizada no trenó, assim como a potência computada no final da fase de aceleração da corrida. A capacidade do atleta de manter a efetividade ao longo da fase de aceleração, entretanto, diminui com a utilização de cargas maiores. Estas informações são importantes para treinadores que pretendem prescrever o treinamento com o uso do trenó, pois com cargas maiores o atleta poderá treinar o direcionamento da aplicação de força na horizontal, principalmente no início da fase de aceleração. Além disso, pode-se usar a potência no final da fase de aceleração para indicar uma carga ótima de treino, ou seja, aquela carga que irá produzir maior potência. O objetivo do segundo artigo foi avaliar o efeito da idade em atletas master (39 a 96 anos) sobre os parâmetros mecânicos do modelo teórico que caracteriza a fase de aceleração da corrida de velocidade. O estudo mostrou que o desempenho da corrida de velocidade diminui linearmente com a idade, com uma queda de aproximadamente 1,10% por ano. Esse declínio foi associado à queda da potência máxima estimada (1,6% por ano), observada nos atletas com idade mais avançada, assim como à queda da força e da velocidade (1% por ano). Além disso, a efetividade desses atletas no início da fase de aceleração também é consideravelmente menor (0,88% de queda por ano) em comparação com atletas mais jovens. Portanto, treinadores devem estar atentos à efetividade de seus atletas master durante a aceleração da corrida, para que eles possam aprender a limitar a queda desse parâmetro e manter uma propulsão mais eficiente.

# ABSTRACT

This thesis aims to analyse two effects that may influence the main parameters of a theoretical model that characterizes the sprinting acceleration phase: the effect of load and the effect of age. The parameters in the model are those that determine the force-velocity and power-velocity relationships, as well as the athlete's ability to orient the application of force on the ground more horizontally (mechanical effectiveness). The purpose of the first paper was to compare the effect of different sled towing loads with the unloaded condition on effectiveness and on the determinants of the force-velocity and power-velocity relationships, during the entire acceleration phase of a sprint. This study showed that mechanical effectiveness increases with load, as well as the power computed at the end of the acceleration phase. However, the ability to maintain effectiveness throughout the acceleration is reduced with the increasing load. These information are useful to coaches who intend to prescribe a sled towing training because it indicates that using heavier sled loads will help in the development of the application of force in a horizontal direction. Furthermore, power at the end of the acceleration phase may be used to determine an optimal training load, i.e. the load that will elicit the highest power. The aim of the second paper was to investigate the effect of age on the mechanical parameters that determine the sprinting acceleration theoretical model, in Master sprinters (39 to 96 years). The results showed a linear age-related decline in sprinting performance with an average decrease of 1.10% per year. The decline was associated to the estimated maximal power reduction (1.6% per year) observed in the older athletes, as well as to the decrease in force and velocity (1% per year). Moreover, effectiveness in the beginning of the acceleration phase is lower in the older athletes (0.88% decline per year) than in the younger ones. Therefore, coaches should be aware of the effectiveness of their Master athletes during the sprinting acceleration phase, so that they can learn to limit its decline and maintain a more efficient propulsion.

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# LISTA DE ABREVIATURAS E SIGLAS

**Em português:**

$D_{RF}$ - capacidade do atleta de limitar a queda da efetividade durante a fase de aceleração

F0 - a máxima força que o sistema é capaz de gerar quando a velocidade é zero

F-V - relação força-velocidade

$P_{ea}$ - potência produzida no final da fase de aceleração

$P_{max}$ - potência máxima

P-V - relação potência-velocidade

RF - razão de força (efetividade mecânica)

$RF_{max}$ - efetividade máxima

V0 - a máxima velocidade que o sistema é capaz de gerar quando a força é zero

**Em inglês:**

$\theta$ - angle of the tow cord

$\mu_K$ - coefficient of kinetic friction

$a_H$ - horizontal acceleration

BM - body mass

CMJ - countermovement jump

CT - contact time

$D_{RF}$ - ability to limit the decrease in RF

ES - effect size

F0 - maximal force the legs can produce, calculated by extrapolation to zero velocity

$F_{aero}$ - aerodynamic friction force

$F_f$ - friction force

$F_H$ - horizontal force

$F_n$ - normal reaction force

$F_{RES}$ - resultant force

FT - flight time

$F_{Tot}$ - total force production

F-V - force-velocity relationship

GRF - ground reaction force

hCMJ - countermovement jump height
hpo - vertical push-off distance
HR - heart rate
hSJ - squat jump height
$k_{leg}$ - leg stiffness
$k_{vert}$ - vertical stiffness
$m_s$ - mass of the sled
$P_{ea}$ - power at the end of the acceleration phase
$P_H$ - horizontal power output
$P_{max}$ - maximal power
P-V - power-velocity relationship
RF - ratio of force (mechanical effectiveness)
$RF_{max}$ - maximal effectiveness
RF-V - ratio of force-velocity relationship
RJ - rebound jump
SD - standard deviation
SJ - squat jump
SSC - stretch-shortening cycle
V0 - maximal velocity the legs can produce, calculated by extrapolation to zero force
$V_H$ - horizontal velocity
$V_{max}$ - maximal velocity
$VO_{2max}$ - maximal oxygen uptake
$VO_{2RM}$ - oxygen uptake of the respiratory muscles
VT1 - first ventilatory threshold
VT2 - second ventilatory threshold

## SUMÁRIO

# 1. INTRODUÇÃO

O aumento do nível de desempenho atlético em uma determinada modalidade esportiva depende de uma série de fatores. Entre eles, os aspectos mecânicos que auxiliam no entendimento da técnica e das causas do movimento têm recebido destaque (JOHNSON; BUCKLEY, 2001; MENDIGUCHIA *et al.*, 2014; MORIN *et al.*, 2015; BENTLEY *et al.*, 2016). De acordo com Bundle e Weyand (2012), o desempenho nos eventos da corrida de velocidade pode ser analisado considerando tanto o *input* quanto o *output* dos músculos esqueléticos que servem como motores mecânicos. O *input* é a energia química que alimenta a contração muscular e o *output* é a força ou potência mecânica que a contração produz.

Mecanicamente, um aumento na velocidade de corrida pode ser alcançado com uma boa aplicação de força contra o solo no sentido horizontal, assim como por meio de uma boa potência muscular (CAVAGNA *et al.*, 1971; JOHNSON; BUCKLEY, 2001; MORIN *et al.* 2011). Muitos estudos tem avaliado o comportamento da relação força-velocidade e potência-velocidade da corrida considerando o sistema multi-articular envolvido na realização do movimento, que por sua vez envolve a atuação de diversos componentes como o nível de recrutamento de diferentes músculos, a arquitetura muscular, a dinâmica dos segmentos, os torques articulares, etc (MORIN *et al.*, 2010; SAMOZINO *et al.*, 2012; MORIN *et al.*, 2012; BOBBERT *et al.*, 2012; RABITA *et al.*, 2015; JARIC, 2015). As variáveis determinantes dessas relações incluem a máxima força que o sistema é capaz de gerar quando a velocidade é zero ($F_0$); a máxima velocidade que o sistema é capaz de gerar quando a força é zero ($V_0$); e a máxima potência que pode ser produzida a partir da relação entre a força e a velocidade (SAMOZINO *et al.*, 2012). A análise desses parâmetros na corrida de velocidade auxilia o treinador na medida em que informa sobre as potencialidades e deficiências dessa relação em cada atleta. Dois atletas podem produzir a mesma potência máxima, mas apresentar um perfil diferente na relação força-velocidade, ou seja, um pode apresentar maior produção de força e menos velocidade e outro menor produção de força e maior velocidade (SAMOZINO *et al.*, 2012; MORIN *et al.*, 2012).

Outra variável que tem recebido destaque recentemente é a efetividade ou razão de força (*RF*) durante a corrida de velocidade. A efetividade é definida como a razão entre a força horizontal e a força total correspondente ou a força resultante dos componentes horizontal e vertical durante o contato do pé com o solo (MORIN *et al.*, 2011). Portanto, um atleta apresenta uma boa efetividade quando ele é capaz de orientar horizontalmente a aplicação de força durante a corrida de velocidade. Rabita *et al.* (2015), em seu estudo, avaliaram a efetividade por meio de uma plataforma de força de 6,60 m durante a fase de aceleração da corrida em velocistas treinados e encontraram que este parâmetro está consideravelmente vinculado ao desempenho. Os autores demonstraram que a capacidade de orientar horizontalmente a aplicação de força é mais importante que a magnitude de força total produzida durante a corrida. Outro parâmetro que se correlaciona com o desempenho é a capacidade do atleta de limitar a queda da efetividade durante a fase de aceleração ($D_{RF}$) (MORIN *et al.*, 2012; MORIN; SAMOZINO, 2016).

Diante da importância das determinantes das relações força-velocidade e potência-velocidade para a performance dos velocistas, pode-se elaborar um modelo teórico da fase de aceleração da corrida de velocidade (MORIN; SAMOZINO, 2016), que é fundamental para que o atleta adquira um bom desempenho nesta modalidade. É importante analisar a interação que ocorre entre estas variáveis, assim como as possíveis alterações que elas podem vir a sofrer dependendo da situação a qual o atleta é submetido. Neste modelo, o desempenho na fase de aceleração depende em grande parte da efetividade na aplicação de força contra o solo:

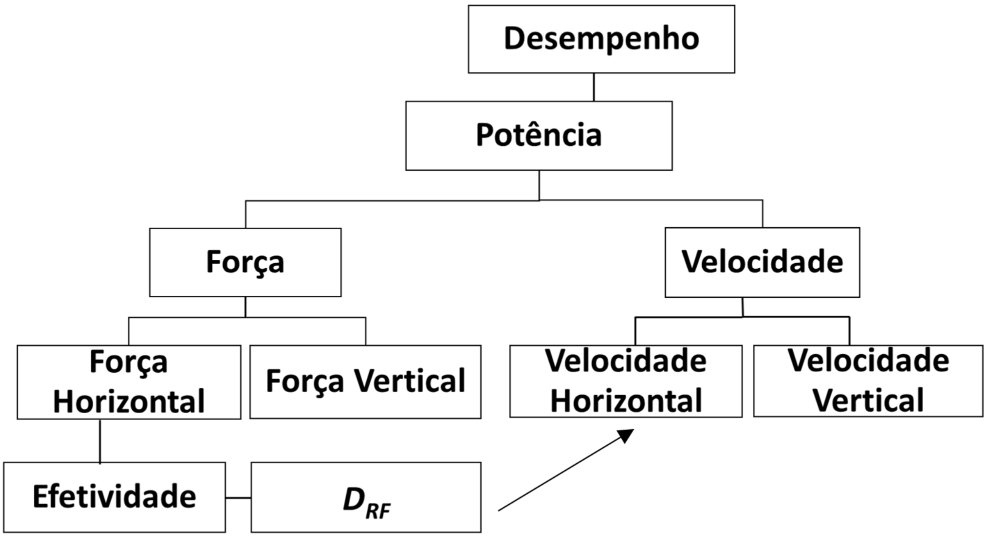

**Figura 1** – Modelo teórico da fase de aceleração da corrida de velocidade.

Diversos fatores podem afetar as variáveis desse modelo como a idade dos velocistas, realizar a corrida com diferentes equipamentos e cargas, atletas de diferentes níveis, a superfície sobre a qual o velocista está correndo, etc. Estudos avaliando o efeito da carga ou da idade durante toda a fase de aceleração da corrida de velocidade, sobre estas variáveis cinéticas que influenciam a performance dos velocistas, tem sido difíceis de encontrar. Com relação ao efeito da carga, Kawamori *et al.* (2014b) avaliaram por meio de uma plataforma de força apenas o segundo contato com o solo após a largada de uma corrida de 5 m, realizada com um trenó preso ao indivíduo por uma corda. A carga colocada nesse trenó correspondia a 10% da massa corporal do indivíduo ou a 30% da massa corporal. Foi encontrado um maior impulso e maior efetividade durante a corrida com a carga de 30% do que com a corrida sem carga. Com relação ao efeito da idade, Korhonen *et al.* (2009) compararam a força de reação do solo entre velocistas jovens e master (17 – 82 anos) durante alguns passos em uma corrida de velocidade. Foi encontrada uma redução da força de reação do solo e uma orientação mais vertical no ângulo de propulsão com o avanço da idade. No entanto, além de apenas alguns passos terem sido analisados, os autores avaliaram apenas a fase de velocidade máxima da corrida.

A dificuldade de se encontrar estudos que tenham avaliado esses efeitos sobre os parâmetros cinéticos do modelo teórico acima apresentado, pode ser resultante da dificuldade de se ter um equipamento apropriado para a mensuração dessas variáveis na situação real da prática da corrida de velocidade. Por exemplo, geralmente não são encontradas plataformas de força com um grande comprimento (30 a 60 m) ou uma série de muitas plataformas de força seguidas umas das outras, para permitir a avaliação cinética de toda a fase de aceleração de um velocista. Mesmo se fossem encontradas, o custo seria muito grande e o acesso a elas por treinadores e atletas seria complicado. Pode-se optar pela realização de diversas corridas, para avaliar os passos correspondentes a diferentes distâncias na fase de aceleração (Cavagna *et al.*, 1971; Rabita *et al.*, 2015). No entanto, recentemente um método simples e acessível foi proposto por Samozino *et al.* (2016) para determinar a efetividade assim como as relações força-velocidade e potência-velocidade durante a fase de aceleração da corrida de velocidade. Este método foi validado ao ser comparado com a corrida realizada sobre a plataforma de força e conta com variáveis de *input* que são fáceis de ser obtidas: massa corporal, estatura e velocidade de corrida ou tempos parciais. A partir dessas variáveis são estimados os parâmetros cinéticos (força, potência, efetividade).

Diante do exposto, é interessante utilizar o método proposto por Samozino *et al.* (2016) para avaliar as variáveis cinéticas determinantes do desempenho da corrida de velocidade, durante toda a fase de aceleração da corrida, sob o efeito de diferentes cargas e sob o efeito do avanço da idade. Em ambas as situações, por exemplo, a aplicação de força durante a corrida pode sofrer alteração, no entanto essa variável pode se alterar mais em uma situação do que em outra. Esta análise pode trazer esclarecimentos acerca dos efeitos que influenciam os parâmetros do modelo teórico, assim como pode auxiliar treinadores a prescreverem melhor o treinamento da corrida de velocidade para os seus atletas.

## 1.1 OBJETIVO GERAL

Analisar o efeito da carga e da idade sobre a efetividade e sobre parâmetros determinantes das relações força-velocidade e potência-velocidade, durante toda a fase de aceleração da corrida de velocidade, em atletas velocistas.

## 1.2 OBJETIVOS ESPECÍFICOS

- Comparar a efetividade máxima ($RF_{max}$) e a $D_{RF}$ entre a corrida realizada sem trenó e a corrida realizada com o trenó com diferentes cargas (20, 30 e 40% da massa corporal);
- Comparar a $F_0$ e a $V_0$ entre a corrida realizada sem trenó e a corrida realizada com o trenó com diferentes cargas (20, 30 e 40% da massa corporal);
- Comparar a potência máxima ($P_{max}$) e a potência produzida no final da fase de aceleração ($P_{ea}$) entre a corrida realizada sem trenó e a corrida realizada com o trenó com diferentes cargas (20, 30 e 40% da massa corporal);
- Comparar o tempo da corrida realizada sem trenó com a corrida realizada com o trenó com diferentes cargas (20, 30 e 40% da massa corporal);
- Analisar o comportamento das relações força-velocidade e potência-velocidade durante toda a fase de aceleração da corrida realizada sem trenó e com trenó com diferentes cargas (20, 30 e 40% da massa corporal);

- Analisar a associação e possível taxa de alteração da $RF_{max}$ e $D_{RF}$ com o avanço da idade, em velocistas jovens e master;
- Analisar a associação e possível taxa de alteração da $F_0$ e $V_0$ com o avanço da idade, em velocistas jovens e master;
- Analisar a associação e possível taxa de alteração da $P_{max}$ com o avanço da idade, em velocistas jovens e master;
- Analisar a associação e possível taxa de alteração no tempo de 20 m de corrida com o avanço da idade, em velocistas jovens e master;
- Analisar o comportamento das relações força-velocidade e potência-velocidade durante toda a fase de aceleração da corrida realizada por velocistas jovens e master.

# 2. REVISÃO DE LITERATURA

## 2.1. EFEITO DA CARGA NA CORRIDA DE VELOCIDADE

Para desenvolver a força muscular e a potência nos membros inferiores, obtendo assim o consequente aumento da aceleração e da velocidade máxima durante a corrida de velocidade, os treinadores acreditam que os programas de treinamento para velocistas devem incluir exercícios específicos de força, nos quais o atleta realiza o movimento esportivo com a adição de uma resistência (ALCARAZ *et al.*, 2008). Nestes exercícios o atleta pode, por exemplo, correr uma determinada distância arrastando um trenó com pesos, preso em sua cintura por meio de uma corda (figura 2), correr usando um cinto com pesos ou correr com um paraquedas fixado a um cinto usado pelo atleta (ALCARAZ *et al.*, 2008; MARTINOPOULOU *et al.*, 2011; ALCARAZ *et al.*, 2012; MARTÍNEZ-VALENCIA *et al.*, 2013). A corrida com o trenó tem sido estudada por diversos pesquisadores e é muito utilizada em programas de treinamento (ALCARAZ *et al.*, 2009; MARTINEZ-VALENCIA, 2015; CROSS, 2016). Além da fixação na cintura, o trenó também pode ser fixado em um ponto no meio das costas, em um colete vestido pelo atleta. Contudo, Alcaraz *et al.* (2008) afirmam que a posição da corda do trenó na cintura do atleta é importante, visto que se a corda estiver em uma altura muito acima do quadril, o atleta compensará esta altura aumentando a inclinação do tronco à frente, para assim conseguir vencer a carga colocada no trenó. O trenó permite que pesos sejam adicionados facilmente, permitindo assim um melhor controle da sobrecarga do exercício (LOCKIE *et al.*, 2003; MURRAY *et al.*, 2005; MAULDER *et al.*, 2008; MARTÍNEZ-VALENCIA *et al.*, 2013; MAKARUK *et al.*, 2013; KAWAMORI *et al.*, 2014a; CROSS, 2016). No entanto, de acordo com Hrysomallis (2012), para que o treinamento resistido seja adequado deve-se ter o cuidado de não adicionar uma carga excessiva, para que o padrão do movimento esportivo não seja afetado de maneira adversa. Por outro lado, se a carga for muito leve, pode não haver estímulo suficiente para promover uma adaptação que melhore o desempenho (MAULDER *et al.*, 2008; CROSS, 2016).

Alcaraz *et al.* (2012) examinaram o efeito de 4 semanas de treinamento resistido utilizando o trenó, comparando com o treinamento realizado sem o trenó, e encontraram por meio de testes de corridas de 50 m, uma melhora do desempenho na fase de aceleração. Esta melhora ocorreu em ambos os grupos, portanto, não houve diferença entre os dois tipos de treino. A ausência de diferenças pode ter ocorrido devido a curta duração do treino (4 semanas), no entanto, ela também pode ter ocorrido devido a uma possível aplicação insuficiente de carga no trenó. Foi utilizada uma carga que causava uma redução de aproximadamente 7,5% na velocidade máxima.

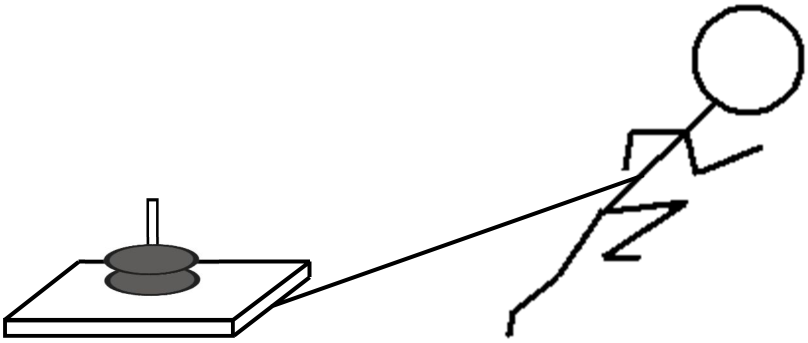

**Figura 2** – Representação esquemática do trenó com pesos, fixado ao atleta.

Tem sido sugerido na literatura que a carga utilizada no trenó não deve causar uma redução na velocidade horizontal do atleta, correspondente a uma quantidade maior que 10% da velocidade máxima, para não prejudicar a técnica de corrida (MAULDER *et al.*, 2008; ALCARAZ *et al.*, 2009). Maulder *et al.* (2008) demonstraram, em seu estudo, que a corrida de 10 m realizada com o trenó com uma carga correspondente a 10% da massa corporal, está dentro deste limite de redução de 10% da velocidade, enquanto que uma carga de 20% da massa corporal, ultrapassou este limite. O exercício com esta carga provocou uma redução no comprimento do passo, nos últimos passos realizados, entretanto, os autores afirmam que alguns benefícios podem ser adquiridos ao treinar com esta carga, apesar das alterações “negativas” que ela provoca na técnica.

Murray *et al.* (2005), em seu estudo, avaliaram a corrida de velocidade com trenó, com cargas variando de 0 a 30% da massa corporal, e encontraram um aumento do tempo de corrida bem como uma redução do comprimento de passada, com o aumento da carga no trenó. No entanto, este efeito pode não ser negativo, pois ele pode trazer benefícios ao longo do treinamento. Segundo Palmieri (1993), é possível que cargas altas desenvolvam a potência da passada por meio do uso forçado de passos mais curtos, ou seja, este efeito provocado pelo exercício de corrida com trenó pode promover uma passada mais potente, como resultado do treinamento resistido.

Prescrever a carga a ser utilizada no trenó apenas com o percentual da massa corporal pode não ser adequado, visto que o atleta A pode ter maior massa, mas desenvolver menos potência, enquanto o contrário acontece com o atleta B. Sendo assim, o atleta B pode ter maior capacidade de correr com a carga do atleta A, por ser mais potente, e da mesma forma a carga do atleta B (mais baixa, por este ter menor quantidade de massa corporal) pode ser mais adequada para o atleta A, pois este produz menos potência. Martínez-Valencia *et al.* (2013) encontraram uma forte correlação entre a potência mecânica de membros inferiores de atletas velocistas e a taxa de aumento no tempo de corrida de 20 e 30 m, durante o exercício com trenó, com diferentes cargas (8% – 18% da massa corporal). Este resultado indicou que o atleta mais potente era aquele que demorava mais para aumentar o tempo de corrida com o aumento da carga. Estar atento a esta variável ao prescrever o treinamento com o trenó, portanto, permite que atletas mais potentes possam se beneficiar da carga utilizada no trenó, ao invés de apenas manter a velocidade que eles possuem, utilizando uma carga que é insuficiente para promover melhora no desempenho (MURRAY *et al.*, 2005).

Poucos estudos tem avaliado a cinética da corrida de velocidade realizada com o trenó (COTTLE *et al.*, 2014; KAWAMORI *et al.*, 2014a; KAWAMORI *et al.*, 2014b; MARTINEZ-VALENCIA *et al.*, 2015; CROSS, 2016). Martinez-Valencia *et al.* (2015) avaliaram a taxa de produção de força durante o primeiro passo de uma corrida de velocidade de 30 m (por meio de uma célula de carga), arrastando um trenó com pesos correspondentes à 10, 15 e 20% da massa corporal. Foi encontrado que o pico da taxa de produção de força nas cargas de 15 e 20% da massa corporal foi significativamente maior do que com a carga de 10%. O estudo de Cottle *et al.* (2014) avaliou a força de reação do solo do pé anterior e posterior em um passo, por meio de duas plataformas de força, durante o início de uma corrida realizada sem trenó e com o trenó com cargas correspondentes à 10 e 20% da massa corporal. Neste estudo, foi encontrado um maior impulso com 20% de carga do que com 10% para o pé anterior e um maior impulso com 20% de carga do que sem trenó para ambos os pés, no entanto, as cargas utilizadas não provocaram efeito na taxa de produção de força.

A dificuldade de se avaliar a cinética da corrida de velocidade com o trenó pode estar na dependência de se ter instrumentos como a plataforma de força, em uma pista de corrida. No entanto, recentemente um método simples foi proposto e validado por Samozino *et al.* (2016) para estimar a força de reação do solo e determinar as relações força-velocidade e potência-velocidade, a partir de mensurações fáceis de se realizar como a mensuração da massa corporal, da estatura e da velocidade ou de tempos parciais. Este método considera a análise cinemática e cinética do centro de massa durante a fase de aceleração da corrida e estima a força horizontal a partir da curva velocidade-tempo e da aceleração. A força vertical aplicada ao centro de massa a cada passo é considerada igual ao peso corporal (DIPRAMPERO *et al.*, 2005; SAMOZINO *et al.*, 2016). O cálculo da força horizontal neste modelo também leva em consideração o arrasto aerodinâmico que deve ser superado durante a corrida, utilizando a estimativa proposta por Arsac e Locatelli (2002). Outro fator que também é importante ser considerado no cálculo da força horizontal, para a corrida realizada com o trenó, é a força de fricção entre o trenó e o solo (LINTHORNE, 2013; LINTHORNE; COOPER, 2013; CROSS 2016). A força de fricção pode ser definida como o produto da força normal (peso total do trenó) e do coeficiente de atrito, e pode ser afetada pelo ângulo da corda que está anexada ao trenó e ao atleta. Se a corda estiver em um ângulo mais verticalizado, a força que puxa o trenó o deslocará mais para cima, reduzindo assim a influência da força normal (LINTHORNE, 2013; CROSS, 2016). Recentemente, uma investigação foi realizada para determinar as mudanças do coeficiente de atrito com diferentes pesos no trenó e diferentes velocidades de corrida (CROSS, 2016). A adição dos pesos não influenciou o coeficiente de atrito, mas a variação de velocidade influenciou, mostrando que o coeficiente de atrito aumenta até aproximadamente 5 $m.s^{-1}$. Dessa maneira, Cross (2016) propôs uma equação para cálculo da força de fricção, considerando que o coeficiente de atrito varia com a velocidade de corrida. Esta equação para o cálculo da força de fricção, portanto, pode ser adicionada ao cálculo da força horizontal durante a fase de aceleração da corrida de velocidade.

Os parâmetros que parecem ser determinantes para a melhora do desempenho da corrida de velocidade são aqueles que caracterizam as relações força-velocidade e potência-velocidade. Estas relações tem sido bem descritas por modelos lineares e parabólicos, respectivamente, caracterizando as capacidades mecânicas de um sistema multi-articular em movimento e descrevendo as alterações na produção de força externa e potência, que ocorrem com o aumento da velocidade de corrida (CAVAGNA *et al.*, 1971; MORIN *et al.*, 2012; SAMOZINO *et al.*, 2012; RABITA *et al.*, 2015; MORIN; SAMOZINO, 2016). As variáveis que determinam essas relações são: a força máxima que o sistema multi-articular é capaz de produzir quando a velocidade é zero ($F_0$); a velocidade máxima que o sistema é capaz de produzir quando a força é zero ($V_0$); a potência máxima produzida que resulta da combinação ótima entre a força e a velocidade (SAMOZINO *et al.*, 2012). Outra variável que tem recentemente se destacado na literatura científica, como determinante de desempenho na corrida de velocidade, é a efetividade ou razão de força (*RF*), que representa a capacidade do atleta de direcionar a aplicação de força contra o solo de maneira mais horizontal (figura 3). A efetividade pode ser calculada por meio da razão entre a força horizontal e a força total produzida ou força resultante (MORIN *et al.*, 2011; RABITA *et al.*, 2015). A capacidade do atleta de limitar a redução da efetividade ($D_{RF}$) ao longo da fase de aceleração da corrida de velocidade, também parece se correlacionar com o desempenho (MORIN *et al.*, 2011; MORIN *et al.*, 2012).

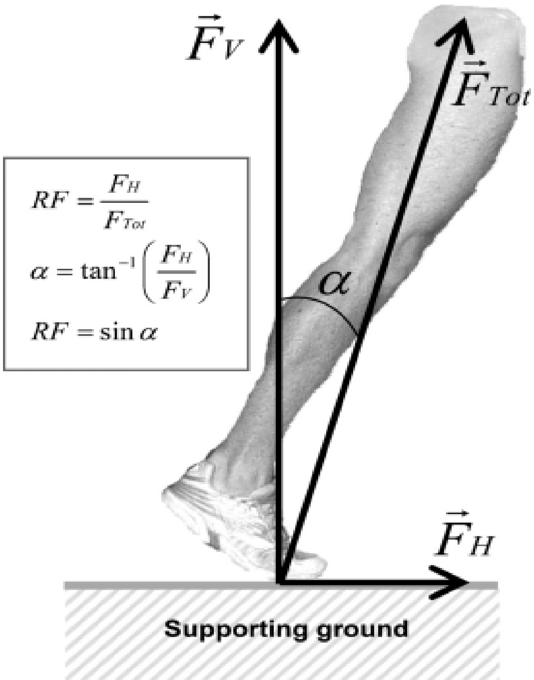

**Figura 3** – Representação esquemática da efetividade ou razão de força (*RF*): capacidade do atleta de direcionar a aplicação de força contra o solo de maneira mais horizontal. Fonte: Morin et al., 2011, p. 1681.

Um estudo realizado por Kawamori *et al.* (2014b) investigou a resposta da força de reação do solo e da efetividade durante o segundo contato do pé com o solo em uma corrida de 5 m, com o trenó com carga de 10 e 30% da massa corporal. Os resultados demonstraram que o impulso horizontal e propulsivo foi maior quando a corrida foi realizada com a carga de 30% do que sem carga. Os autores atribuíram esse aumento ao maior tempo de contato do pé com o solo e não à maior produção de força, porque os valores médios da força horizontal e propulsiva, assim como o valor de pico da força propulsiva, não foram significativamente diferentes entre a corrida sem carga e com carga de 30%. Como os autores encontraram uma efetividade maior para a corrida com carga de 30%, eles também acreditam que o maior impulso possa ser explicado por um melhor direcionamento horizontal da aplicação de força do que por uma maior magnitude da produção de força resultante.

Diante da revisão apresentada, percebe-se que são necessários mais estudos que comparem em velocistas o comportamento das relações força-velocidade e potência-velocidade, assim como a efetividade, entre diferentes cargas durante toda a fase de aceleração da corrida de velocidade realizada com o trenó. Estas avaliações podem trazer esclarecimentos acerca deste método de treinamento e da maneira como ele influencia essas variáveis que são determinantes do desempenho da corrida de velocidade.

## 2.2. EFEITO DA IDADE NA CORRIDA DE VELOCIDADE

Um tópico que tem recebido atenção na comunidade científica é o processo de envelhecimento em atletas master. Qual o efeito da idade nos aspectos biomecânicos e fisiológicos destes atletas, e que diferenças aparecem com relação aos atletas jovens nas diversas modalidades esportivas, são questões que os pesquisadores buscam responder ao abordarem este tópico (HAMILTON, 1993; KORHONEN *et al.*, 2006; LOUIS *et al.*, 2009; RANSDELL *et al.*, 2009; KORHONEN *et al.*, 2009).

As categorias do campeonato master são definidas por idade e geralmente partem de 35-39 anos, sendo divididas com uma diferença de 5 anos (por exemplo, 35-39; 40-44; 45-49, etc.), embora a definição da idade em que o atleta se torna um atleta master varie de acordo com a modalidade esportiva. Segundo o estudo de Ransdell *et al.* (2009), baseado em recordes mundiais dos esportes de natação, ciclismo e corrida, após a idade de 55 anos o declínio no desempenho aumenta exponencialmente, sendo mais pronunciado em mulheres do que em homens, bem como mais pronunciado durante a corrida do que durante a natação e o ciclismo. A partir dos 80 anos de idade, este declínio parece se tornar ainda mais significativo (KORHONEN *et al.*, 2009; RANSDELL *et al.*, 2009). As variáveis que parecem ser mais sensíveis às mudanças no desempenho anaeróbico, como durante a corrida de velocidade, são as determinantes da velocidade e aquelas relacionadas às características neuromusculares (RANSDELL *et al.*, 2009).

Analisando os recordes dos atletas master nos 100 m de corrida, Korhonen *et al.* (2009) afirmam que a velocidade média de corrida parece reduzir 32,5% (0,56% por ano) no decorrer de 60 anos (de 10,32 m/s aos 22 anos a 6,97 m/s aos 80 anos). Um outro estudo de Korhonen *et al.* (2003), que avaliou parâmetros cinemáticos na corrida dos 100 m, durante o XII Campeonato Máster Europeu, demonstrou que a distância necessária para alcançar a velocidade de pico, avaliando atletas homens de 40 a 49 anos (45 m), foi significativamente diferente daquela observada nos atletas homens de 80 a 89 anos (25 m). Contudo, o tempo para alcançar a velocidade de pico (4,4 a 6,08 s) não foi significativamente diferente entre os grupos. Para as atletas mulheres de 50 a 59 anos (35 m), a distância para alcançar a velocidade de pico foi significativamente diferente daquela observada nas mulheres de 70 a 79 anos (20 m), e também não foi encontrada diferença com relação ao tempo (4,15 a 5,58 s).

As determinantes cinemáticas da velocidade de corrida, a frequência e o comprimento da passada, apresentam um comportamento distinto dependendo da fase da corrida dos 100 m. Velocistas jovens, de elite, geralmente alcançam a frequência de passada máxima entre os 10 e 20 m iniciais, onde o comprimento de passada corresponde a 75% do valor observado na fase de velocidade máxima. Entretanto, nos últimos 10 – 20 m, a frequência de passada parece diminuir, enquanto o comprimento de passada aumenta (KORHONEN, 2009). A velocidade máxima de corrida assim como o maior comprimento de passada parecem depender da capacidade do atleta de produzir de força durante o curto tempo de contato do pé com o solo (MERO; KOMI, 1986; WEYAND *et al.*, 2000; KORHONEN *et al.* 2009). Hamilton (1993) avaliando atletas master dos 100 m durante o Campeonato Mundial Master, por meio de uma câmera posicionada por volta dos 60 m, não encontrou diferença na frequência de passada, embora tenha encontrado uma redução significativa do comprimento de passada com o avanço da idade. O estudo concluiu que a alteração na velocidade ocorre principalmente devido à redução do comprimento da passada, em vez de ocorrer devido à quantidade de tempo utilizado em cada passada. A redução do comprimento de passada, assim como a manutenção da frequência da passada, observada nos atletas master velocistas, provavelmente ocorre devido a uma força de reação do solo reduzida, durante a propulsão na fase de contato do pé com o solo, bem como uma baixa taxa de produção de força. A redução no tamanho das fibras musculares rápidas, a transição de fibras rápidas para fibras lentas e uma menor velocidade de encurtamento, contribuem para o surgimento destes resultados (KORHONEN *et al.*, 2006; KORHONEN *et al.*, 2009; ARAMPATZIS *et al.*, 2011; BRISSWALTER; NOSAKA, 2013).

Mesmo diante das reduções observadas nos parâmetros mecânicos com o avanço da idade, nos velocistas master, esses atletas demonstram maior tamanho de fibra muscular, uma intacta força máxima normalizada por área de secção transversal no nível da fibra muscular e maior força máxima e explosiva, em comparação com sujeitos de mesma idade não treinados (KORHONEN *et al.*, 2006). Pearson et al. (2002) compararam o efeito do envelhecimento sobre a força muscular e a potência em atletas master levantadores de peso e sujeitos não treinados (40 – 89 anos), e os resultados mostraram que em ambos os grupos houve um declínio da força e da potência de membros inferiores com o avanço da idade (atletas de 70 anos produziram 62% da potência produzida por jovens). No entanto, os levantadores de peso eram significativamente mais fortes e mais potentes do que os sujeitos não treinados. Um atleta de 85 anos produziu uma potência que era equivalente a de um sujeito de 65 anos não treinado. Portanto, embora o declínio de desempenho seja inevitável, idosos altamente treinados ainda são capazes de competir inclusive em idade correspondente a 95 anos e as pesquisas realizadas com estes atletas podem trazer um grande aprendizado, visto que eles otimizam seu condicionamento físico, revelando o desempenho que pode ser alcançado durante o envelhecimento (KORHONEN *et al.*, 2006; KORHONEN, 2009).

Atletas master servem como exemplo de indivíduos que resistem a esse declínio natural decorrente do envelhecimento. Com a prática esportiva, esses atletas apresentam uma imagem ativa, vigorosa e independente em vez de uma imagem passiva, frágil e dependente, o que faz com que sejam considerados como modelo de envelhecimento bem sucedido (RITTWEGER *et al.*, 2004; DIONIGI, 2006; RITTWEGER *et al.*, 2009; RANSDELL *et al.*, 2009). Segundo Izquierdo e Cadore (2014), o treinamento de alta velocidade voltado para desenvolvimento da potência muscular pode ser realizado junto com outros tipos de treino (equilíbrio, resistência, força) e trazer benefícios inclusive aos idosos frágeis, que possuem uma condição física bastante fraca. Sugere-se, nesse caso, uma familiarização prévia com exercícios em velocidade confortável, em intensidades baixas e moderadas, para que o idoso adquira os primeiros ganhos e aprenda os exercícios. Kusy e Zielinski (2015) afirmam que os termos “exercício” e “treinamento” nas pesquisas relacionadas à saúde e envelhecimento, geralmente estão associados ao treinamento de resistência. Os autores indicam que o treinamento de *sprint* a longo prazo também pode trazer benefícios à saúde do idoso, como a melhora na densidade mineral óssea, massa muscular e função neuromuscular, sendo que esse benefícios se sobressaem em relação aos possíveis riscos deste tipo de treino (como, por exemplo, possíveis lesões). Atletas master que competem em corrida de velocidade têm demonstrado melhora no desempenho ao longo dos anos. Para a corrida de 100 m rasos, os homens jovens melhoraram a sua média de 10,05 s em 1975 para 9,75 s em 2013, enquanto os homens idosos (75 – 79 anos) melhoraram seu tempo de 14,80 s em 1977 para 13,75 s em 2013. Para as mulheres, a melhora foi ainda mais pronunciada: jovens melhoraram de 11,13 s em 1975 para 10,79 s em 2013, enquanto as idosas (75 – 79 anos) melhoraram de 19,25 s em 1981 para 15,94 s em 2013 (AKKARI *et al.*, 2015).

Devido à importância que o treinamento de velocidade tem assumido na população idosa, seria interessante poder avaliar determinantes do desempenho da corrida de velocidade, como as variáveis que caracterizam as relações força-velocidade e potência-velocidade, em atletas master que estão acostumados com este tipo de treino. Allison *et al.* (2013) compararam essas relações entre sujeitos idosos e jovens, não treinados, durante o exercício de *Leg Press*. Os sujeitos idosos demonstraram valores mais baixos nas relações força-velocidade e potência-velocidade, sendo que a potência máxima foi 28% menor nos sujeitos idosos, a velocidade foi 11% menor e a força ótima 20% menor, sendo que a redução da força, contribuiu mais para a redução da potência. A análise dessas variáveis é difícil de encontrar em atletas master velocistas, especialmente durante a fase de aceleração, em situação real de treino ou competição. O estudo de Korhonen *et al.* (2009) avaliou a força de reação do solo (4 contatos do pé com o solo em um sistema de 9 plataformas de força) em velocistas master, durante a fase de velocidade máxima da corrida, e foi demonstrado que a queda da velocidade de corrida com o avanço da idade se deve a uma menor produção de força e a uma consequente redução do comprimento de passada e maior tempo de contato do pé com o solo. A aplicação da força durante o contato do pé com o solo também mostrou se tornar mais verticalizada com o avanço da idade, durante a fase de velocidade máxima da corrida.

A análise da relação força-velocidade e potência-velocidade, assim como a avaliação da capacidade do atleta master de orientar horizontalmente a aplicação de força durante a fase de aceleração da corrida, se faz necessária para trazer esclarecimentos acerca das alterações que o efeito da idade pode provocar nessas variáveis. Os resultados deste tipo de investigação podem auxiliar treinadores a preparar de maneira mais adequada o treinamento de atletas master que visam se especializar em corrida de velocidade.

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# 4. ARTIGO I

## Effect of Weighted Sled Towing on Sprinting Mechanics

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### Abstract

This study aimed to compare the components of the force-velocity (*F-V*) and power-velocity (*P-V*) profiles and the mechanical effectiveness of force application (*RF*) between different sled towing loads during the entire acceleration phase of a weighted sled sprint. Eighteen sprinters performed four 50 m sprints in different conditions: unloaded; with a load corresponding to 20% of the athlete's body mass (BM); 30% BM and 40% BM. Data were collected with five video cameras and the images were digitized to obtain velocity from the derivation of the center of mass position. *F-V* and *P-V* components and *RF* were estimated from sprinting velocity-time data for each load using a recently validated field method. The theoretical maximal velocity ($V_0$) decreased with load when compared to the unloaded condition (effect size (ES) = 1.02 for 30% BM; ES = 1.10 for 40% BM). The theoretical maximal horizontal force ($F_0$) and maximal power ($P_{max}$) were not different between conditions, however power at the end of the acceleration phase ($P_{ea}$) increased with load (ES = 2.22 – 3.25) as well as the maximal mechanical effectiveness ($RF_{max}$; ES = 0.57 – 0.87). The linear decrease in *RF* ($D_{RF}$) was different between 30 or 40% BM and the unloaded condition (ES = 0.74 and 0.66). A better effectiveness may be developed with 40% BM load in the beginning of the acceleration and the different loads induced changes in the components of the F-V and P-V relationships, allowing a more accurate determination of optimal loading conditions for maximizing power.

**Key Words:** performance, ratio of force, running, resisted sled sprint

## Introduction

Speed development is a determinant factor for success in sprinting events. The prescription of resistance training, including sport specific movement, has often been applied by trainers to improve the performance of their athletes through the achievement of higher speeds. Different training methods have been used to add resistance to an athlete's sprinting, such as wearing a weighted belt, towing a parachute or towing a weighted sled (Alcaraz et al., 2008; Martinopoulou et al., 2011; Martinez-Valencia et al., 2013; Petrakos et al., 2016).

Using a sled may be the best method for sprinters since this device exert a horizontal force on the athlete (which is different than using a weighted belt) and it allows the addition of an optimal external overload (Young et al., 2001; Alcaraz et al., 2008). A chest or waist harness and cord are used to attach the sled to the athlete and a series of sprints are performed towing the sled with the addition of a specific load (Lockie et al., 2003; Petrakos et al., 2016). Some studies evaluating sled towing with different loads suggest that the athletes should not be slowed down more than 10% in their velocity (i.e. loads should not be heavier than 10-13% body mass (BM)) because it would bring negative alterations on sprint technique (Murray et al., 2005; Alcaraz et al., 2008). However, heavier loads (>20% BM) are necessary to provide sufficient stimulus to increase force production and speed development during the acceleration phase (Palmieri, 1993; Lockie et al., 2003; Maulder et al., 2008; Cottle et al., 2014; Kawamori et al. 2014b). The training effects depend on the load applied and the level of the participants. A light load may be enough for an untrained subject, but it will not be sufficient for trained sprinters who need to improve their performance (Petrakos et al., 2016).

Recent studies have described sprint mechanics during the acceleration phase analysing the force-velocity (*F-V*) and power-velocity (*P-V*) profile and its theoretical parameters as the maximal velocity the legs can produce, calculated by extrapolation to zero force ($V_0$) and the maximal force the legs can produce, calculated by extrapolation to zero velocity ($F_0$), characterizing the mechanical limits of multi-joint movements, influenced by muscle mechanical properties, neural activity and joint configuration (Samozino et al., 2012; Morin et al., 2012; Rabita et al., 2015; Jaric, 2016). The theoretical maximal horizontal force does not show correlation with 100 m sprint performance whereas the theoretical maximal velocity shows (Morin et al., 2012). Improvement in sprint performance has been associated with an efficient application of force in the horizontal plane, rather than with greater magnitude of the resultant force production (Morin et al., 2011; Morin et al., 2012; Rabita et al., 2015). The orientation of force application can be evaluated from the level of effectiveness an athlete demonstrates. Effectiveness or the ratio of forces (*RF*) is defined as the ratio of the horizontal force ($F_H$) to the corresponding total force production ($F_{Tot}$) averaged over the stance phase (Morin et al., 2011). Furthermore, the ability to limit the decrease in *RF* ($D_{RF}$) with increasing speed during the acceleration phase is highly correlated to sprint performance (Morin et al., 2011). Hence, it is more important for a sprinter to be able to direct the application of force onto the ground horizontally and limit the decrease in *RF* than being able of producing higher amounts of total force.

The evaluation of *RF* or kinetic parameters during the entire acceleration phase of a sled towing sprinting with different loads is difficult to find in the literature. The methods for the analysis of these parameters would involve using a device such as a force plate that should be 30-60 m long (or a sequence of force plates positioned one behind the other), to permit the evaluation of the entire acceleration phase. To our knowledge no such device exists and even if there was such device, it would be very expensive and few people would have access to its use (Samozino et al., 2016). Recently, a valid simple method to determine *F-V*, *P-V* and *RF* was proposed for sprint running in overground conditions showing a very good agreement with the force plate measurement (Samozino et al., 2016). This method can be easily used and it requires only the collection of anthropometric and spatiotemporal variables, such as body mass, stature and instantaneous velocity during the acceleration phase of the sprint run.

To our knowledge, few studies analysed kinetic parameters during resisted sled sprint (Kawamori et al., 2014a, b; Martinez-Valencia et al., 2015; Bentley et al., 2016). From these studies, some did not analysed track sprinters (Kawamori et al., 2014a, b) and also the ground reaction force (GRF) or rate of force development was analysed using only one step at the beginning of the acceleration phase (Kawamori et al., 2014b; Martinez-Valencia et al., 2015; Bentley et al., 2016) or few steps 8 m from the start (3 force plates giving a total length of 2.7 m; Kawamori et al., 2014a). The comparison of these parameters between different loads (especially the *RF* parameter) during the entire acceleration phase of a weighted sled sprint, in track sprinters, could give further insight on the improvements of sprint performance, helping coaches to better prepare their athletes for sprinting events. Hence, the aim of this study was to compare the mechanical variables associated with the *F-V* and *P-V* profile as well as *RF* between different sled towing loads and the unloaded condition, during the entire acceleration phase of the sprint running. The primary hypothesis of this study was that the mechanical power would be major when towing a sled, in comparison to unloaded condition, at the end of the acceleration phase at which inertial forces are remarkably lower than at starting phase. We also hypothesized that *RF* would increase with greater loads, due to the unavoidable additional work from the sled (Linthorne, 2013).

## Materials and methods

### *Subjects and experimental protocol*

Eighteen athletes volunteered to participate in this study (12 men and 6 women; age: 18.4 ± 3.84 years; body mass: 65.8 ± 11.3 kg; height: 1.70 ± 0.11 m; body fat: 12.2 ± 2.52%). They were informed about the experimental procedures and gave their written informed consent, which was approved by the local Ethical Committee. All participants were trained sprinters who were competing mainly in 100 m events (n = 13; 400 m: n = 5) and they were free from any lower extremity injury that would prevent them from performing the tests. Their mean performance in the current season was 843 ± 145 IAAF points (Spiriev & Spiriev, 2014).

The experimental protocol comprised four 50 m sprints performed in four different conditions: without a load and towing a sled with 20, 30 and 40% BM. These loads were chosen, especially 30 and 40% BM, to contrast with the recommendation of less than 20% BM (Alcaraz et al., 2008), since heavier loads may be a better stimulus to the athletes (Kawamori et al., 2014b; Petrakos et al., 2016). A reliability test was conducted before the study and showed that the sled protocol was reliable (ICC = 0.87-0.94). The order of the trials was randomized and 15 minutes of passive rest were allowed between conditions. The 50 m sprint distance was chosen after a pilot study to guarantee that all athletes would complete the entire acceleration phase. All athletes were familiarized with weighted sled towing and before the test they performed their standard 30 minutes warm up consisting of dynamic stretching, jogging, technical drills and submaximal sprints. They were asked not to participate in any physical exercise before the test and all participants performed the test on the same period of the day on an outdoor synthetic track *(Tartan™)*. No external factor such as temperature or the wind differed considerably between the subjects' test. The sled was attached to a harness by a cord with 2.7 m at the point of the athlete's waist. The sled's weight was 5.2 kg and an additional weight was placed on the sled to obtain the appropriate testing load for each athlete.

Data were collected using five high-speed video cameras (CASIO EXILIM FH25, Tokyo, Japan) placed in a perpendicular position to the sagittal plane of motion, with overlapping fields to allow the analysis of the entire sprint. An LED system positioned over the top of each lens of the camera and triggered at the same time allowed synchronization of the five cameras. Distance between cameras and the midline of the running lane was 10.54 m and the distance between cameras was on average 11 m. Each camera recorded 10 m of the sprint at a sample frequency of 120 Hz. Reflective markers were placed on nine anatomical references: fifth metatarsal of the foot; heel; lateral malleolus; lateral condyle of the femur; greater trochanter; styloid process of the ulna; lateral epicondyle of the humerus; acromion of the scapula and temporal bone. Before each test and after the adjustment of the cameras two 2 m rods with two reference points were recorded for each camera and they were placed in the field of view so that one could be viewed in the other camera (toward the extremity of each camera). The recorded images were uploaded to a computer and analysed by digitization frame by frame and subsequent reconstruction of each sprint using SkillSpector (1.3.2, Odense, Denmark). A device producing sound and light when triggered was use to mark the athletes start and the beginning of the digitizing process (when the light was turned on). A cone was placed on the finish line to mark the end of the sprint. Position data were exported in text files and filtered using a fourth-order Butterworth filter with a cut-off frequency of 3 Hz using LabView 2013 software (National Instruments, Austin, USA). The calculation of the center of mass was done from the anthropometric data proposed by Winter (1990) using the segment mass and length (proximal) for the segments head-neck-trunk; forearm-hand; upper arm; thigh; shank and foot. Velocity for each athlete and condition was obtained from the derivation of the center of mass position.

### *Mechanical Variables*

After exporting the velocity data to an Excel spreadsheet, the calculations proposed recently by Samozino et al. (2016) to estimate mechanical variables such as force, power and effectiveness (*RF*) were done. This is a valid and reliable method that was compared with the gold standard method of using force plates to measure these mechanical variables. The calculations were based on the athlete’s body mass, height and running velocity. Raw velocity-time data (Figure 1) were very well fitted by an exponential function (diPrampero et al., 2005; Morin et al., 2006; Samozino et al., 2016), which is shown below:

$$v(t) = v_{\max}(1 - e^{-t/\tau}) \tag{1}$$

where $v_{max}$ is the maximal velocity at the end of the acceleration phase in m.s$^{-1}$ and $\tau$ is the acceleration time constant in seconds. This function was used to decrease the noise and present a more stable velocity-time curve. From the instantaneous velocity the horizontal acceleration was obtained ($a_H$) and then the net horizontal antero-posterior GRF ($F_H$) applied to the center of mass was modeled in accordance with the following equation:

$$F_H = (m+m_s)a_H + F_{aero} + F_f \tag{2}$$

where $m$ is the athlete's body mass and $m_s$ is the mass of the sled, in kg; $F_{aero}$ is the estimated aerodynamic friction force acting on the athlete-sled system during sprint running (Arsac e Locatelli, 2002); and $F_f$ is the friction force acting on the base of the sled. For the estimation of friction force a recent reliable equation was proposed (Cross, 2016), considering that the coefficient of friction is dependent on instantaneous velocity:

$$Ff = (\mu_K \cdot F_n)/(\cos\theta + \mu_K \sin\theta) \tag{3}$$

where $\mu_K$ is the coefficient of kinetic friction and $F_n$ is the normal reaction force or the total weight of the sled determined by $m_s$ multiplied by acceleration due to gravity (9.81 m.s$^{-2}$). The coefficient of friction can be estimated as follows:

$$\mu_K = -0.0052v_h^2 + 0.0559v_h + 0.3184 \tag{4}$$

The angle of the tow cord ($\theta$) during the sprint was obtained from video analysis using the software Kinovea (0.8.15, Montceau-les-Mines, France).

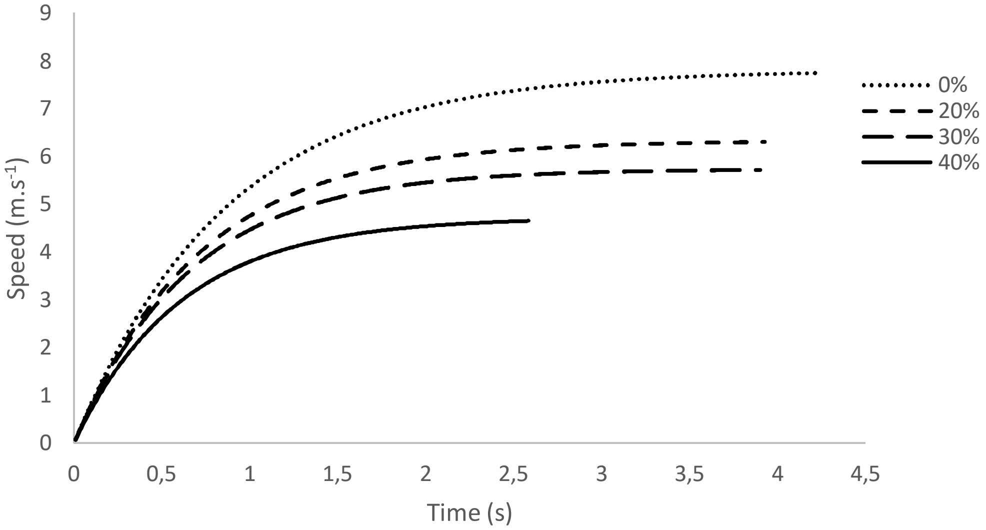

*Fig 1.* Sprinting velocity as a function of time during the entire acceleration phase, for each condition.

Power in the horizontal direction was calculated as the product of instantaneous $F_H$ and $v$. Maximal power in W.kg$^{-1}$ ($P_{max}$) was estimated from a validated equation (Vandewalle et al., 1987):

$$P_{\max} = \frac{F_0 V_0}{4} \tag{5}$$

Force-velocity and power-velocity relationships for each athlete were fitted with least-square linear and second-order polynomial regressions, respectively (Morin et al., 2010; Morin et al., 2012). From the extrapolation of the force-velocity relationship to zero velocity and zero force, the theoretical maximal force ($F_0$) and velocity ($V_0$) were obtained, respectively. The effectiveness or RF was computed for each step as the ratio of $F_H$ to the corresponding resultant GRF ($F_{RES}$), as follows (Morin et al., 2011):

$$RF = \frac{F_H}{F_{RES}}.100 = \frac{F_H}{\sqrt{F_H^2 + F_V^2}} \tag{6}$$

where $F_V$ is the mean net vertical GRF acting on the center of mass over each step and modelled over time as equal to body weight (diPrampero et al., 2015). The slope of the linear decrease in RF over the entire acceleration phase was also obtained ($D_{RF}$). These two variables were computed from $F_H$ and $F_V$ modeled for $t > 0.3$ s (Morin et al., 2011; Rabita et al., 2015). The maximal value of *RF* ($RF_{max}$) was also obtained from t > 0.3 s.

*Statistical analysis*

Data are presented as mean ± standard deviation (SD). Normality was tested applying the Shapiro-Wilk test and an ANOVA for repeated measures was applied to compare the four different loading conditions. If the distribution was not normal, a Friedman test was applied to compare the sprint conditions. A Bonferroni test was used to analyze the possible differences between loads. The statistical procedures were performed using SPSS 24.0 and the statistical significance was set at $p<0.05$. The effect size (ES) Cohen's *d* coefficient was also calculated to assess the magnitude of differences between experimental conditions. The ES was interpreted as trivial (< 0.2), small (0.2-0.6), moderate (0.6-1.2), or large (> 1.2) (Drinkwater et al., 2007; Maulder et al., 2008; Hopkins et al., 2009).

## Results

Mechanical variables for each load are shown in Table 1. The results showed that the maximal velocity an athlete is able to reach (theoretical maximal velocity – $V_0$) decreased significantly with load (ES = 1.02 for 30% BM; ES = 1.10 for 40% BM) when compared with the unloaded condition (except between 0% and 20% BM, although a lower value was found for 20% compared with 0%). Towing a sled with loads of 20, 30 and 40% BM had no significant effect on $F_0$, however an increase was found in the mean values with increasing load, opposing the decrease in $V_0$. No significant effect was observed in $P_{max}$, however when power was computed at the end of the acceleration phase ($P_{ea}$; an average of the last second of the acceleration phase) a significant increase was found with increasing load (loading conditions compared to unloaded condition: ES = 2.22 – 3.25). The maximal mechanical effectiveness ($RF_{max}$) of force application increased significantly with load (ES = 0.57 – 0.87) and the decrease in the ratio of force ($D_{RF}$) during the acceleration phase was significantly different between 30% or 40% load and the unloaded condition (ES = 0.74 and 0.66, respectively), indicating that with heavier loads the ability to limit the decrease in *RF* is reduced. The 50 m sprint time showed a significant increase with the increasing load (ES = 1.64 – 2.99). *P-V*, *F-V* and *RF-V* relationships are shown in Figures 2, 3 and 4, respectively.

Table 1. Sprint running mechanics during the entire sprint acceleration. Data are presented as mean *(SD)*, for each load (0%; 20%; 30%; 40%).

| | **Mean** ***(SD)*** |
|---|---|
| **Theoretical maximal velocity $V_0$ (m.s$^{-1}$)** | |
| *0%* | 7.35 *(1.08)* |
| *20%* | 6.93 *(1.10)* |
| *30%* | 6.26 *(1.06)* †* |
| *40%* | 6.04 *(1.28)* †* |
| **Theoretical maximal horizontal force $F_0$ (N.kg$^{-1}$)** | |
| *0%* | 8.29 *(2.29)* |
| *20%* | 8.62 *(1.87)* |
| *30%* | 9.49 *(2.43)* |
| *40%* | 9.52 *(2.82)* |
| **Computed maximal power output $P_{max}$ (W.kg$^{-1}$)** | |
| *0%* | 15.0 *(3.93)* |
| *20%* | 14.7 *(2.85)* |
| *30%* | 14.5 *(3.22)* |
| *40%* | 13.9 *(3.70)* |
| **Computed power output at the end of the acceleration phase $P_{ea}$ (W.kg$^{-1}$)** | |
| *0%* | 2.68 *(1.72)* |
| *20%* | 7.43 *(2.49)** |
| *30%* | 8.69 *(1.97)** |
| *40%* | 9.46 *(3.06)* † ◊* |
| **Computed ratio of force $RF_{max}$ (%)** | |
| *0%* | 49.8 *(8.3)* |
| *20%* | 53.9 *(6.04)** |
| *30%* | 56.3 *(6.48)* †* |
| *40%* | 56.7 *(8.02)* †* |
| **Computed decrease in the ratio of force $D_{RF}$** | |
| *0%* | - 0.106 *(0.034)* |
| *20%* | - 0.112 *(0.036)* |
| *30%* | - 0.137 *(0.049)*†* |
| *40%* | - 0.137 *(0.057)** |
| **Time 50 m (s)** | |
| *0%* | 6.78 *(0.65)* |
| *20%* | 8.06 *(0.89)** |
| *30%* | 8.94 *(1.13)* †* |
| *40%* | 9.91 *(1.33)* † ◊* |

** significantly different from 0% load*

*† significantly different from 20% load*

*◊ significant difference between 30% and 40%*

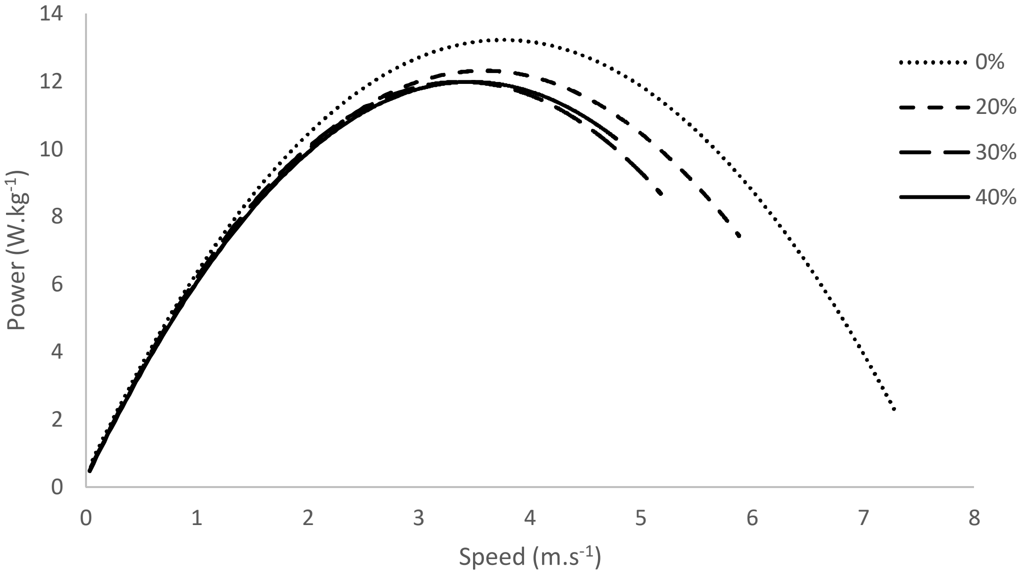

*Fig 2.* Sprinting power as a function of speed during the entire acceleration phase, for each condition.

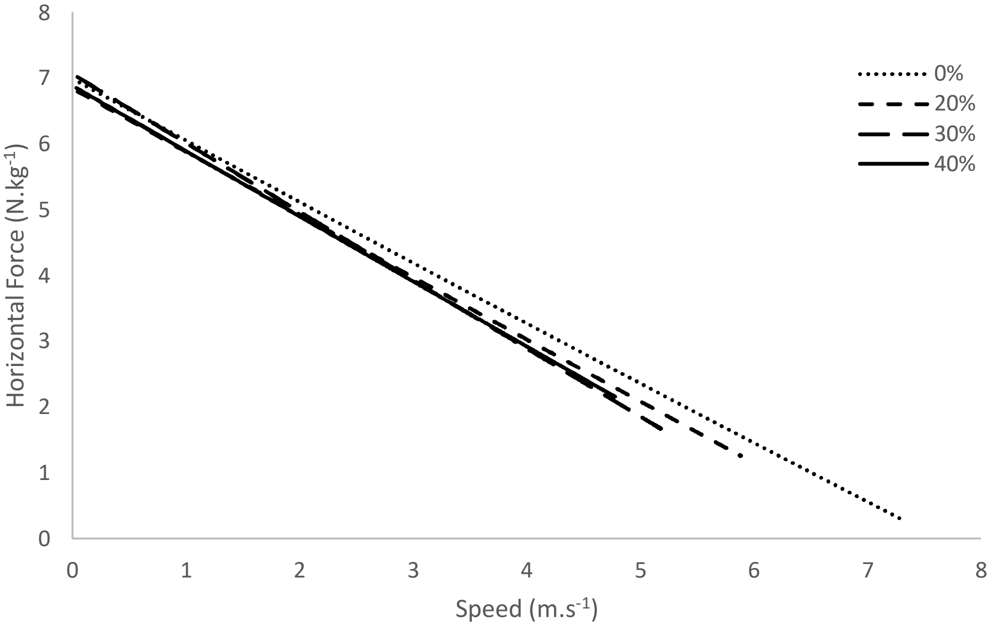

*Fig 3.* Force-velocity relationship during the entire acceleration phase, for each sprinting condition.

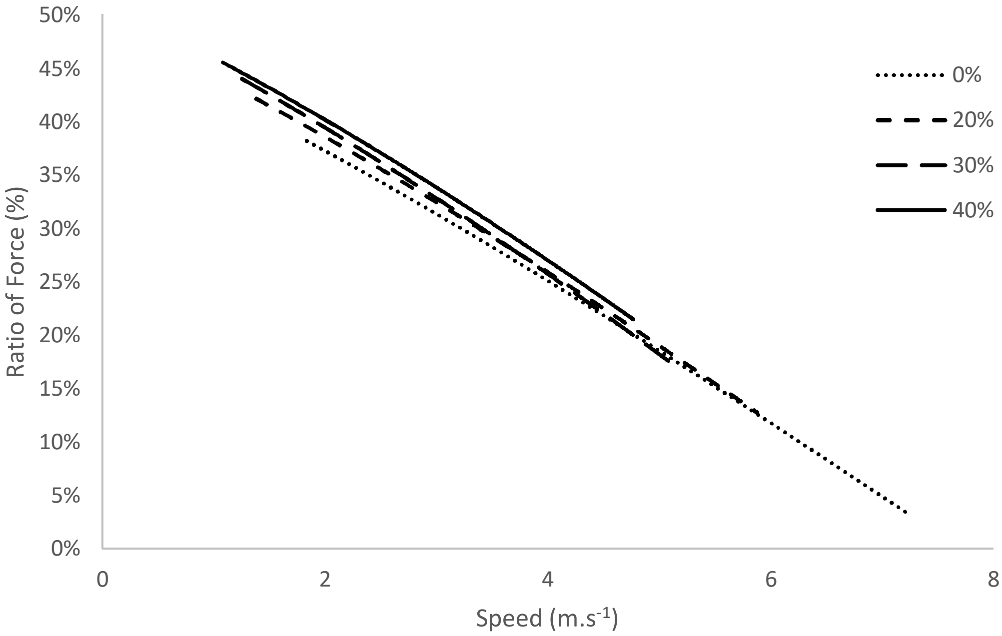

*Fig 4.* Ratio of force (*RF*) as a function of speed during the entire acceleration phase, for each sprinting condition. The $D_{RF}$ index is the slope of the decrease in RF with speed (in this figure: 0% = -0.085; 20% = -0.085; 30% = -0.091; 40% = -0.084).

## Discussion

The main findings of this study are: (1) maximal mechanical effectiveness of force application increases with load and the ability to limit the decrease in effectiveness during the sprinting acceleration phase decreased when towing a sled with 30% or 40% BM compared with the unloaded condition; (2) power computed at the end of the acceleration phase was greater with the increasing load. It is worth noting that this study included sled towing loads (30 and 40% BM) that were heavier than the recommended load of less than 20% BM (Alcaraz et al., 2008).

We accept our first hypothesis that mechanical power increases more critically at the end of the acceleration phase than at the initial phase, when towing a weighted sled. Some important details deserve comment. Firstly, the notoriously greater mechanical power at end of acceleration with sled, in contrast with the unloaded condition, may be due to a fractional increased resistance of the sled to propel the body forward in this phase. This is presumably due to basic differences in the mechanical work production during the entire acceleration. At the start there is a huge necessity to vary the kinetic energy from zero to maximal speed, whereas at final acceleration the work done to reaccelerate the body forward is extremely reduced (Cavagna et al., 1971, diPrampero et al., 2005). Therefore, the constant level of external horizontal force transmitted to the sprinter's waist play a more important role on mechanical power generation during the second half of the acceleration. Our second hypothesis is also supported: the effectiveness or technical ability of force application was enhanced with weighted sled.

The effectiveness of sprint running have been assessed by few studies to show the ability of the sprinter to orient the force production more horizontally, thus improving his sprint performance (Morin et al., 2011; Morin et al., 2012; Rabita et al., 2015). Rabita et al. (2015) evaluated sprint acceleration mechanics and found that the effectiveness of force application onto the ground is a great determinant of the performance of highly trained sprinters, being more important than the magnitude of total force production. However, studies evaluating this parameter in resisted sled sprinting during the entire acceleration phase are difficult to find. Kawamori et al. (2014b) investigated the GRF of the second ground contact after the start of a 5 m sprinting towing a weighted sled with loads equal to 10 and 30% BM. The authors found greater ratio of forces as well as greater net horizontal impulse for the load of 30% BM than the unloaded condition. It was indicated that the greater net horizontal impulse was probably due to longer contact time rather than greater force production due to a lack of significant difference in horizontal GRF between the 30% condition and the unloaded condition. These findings are in agreement with the ones found in the present study. Our results showed that the application of force in a forward direction increased with heavier loads and that towing a weighted sled with different loads had no significant effect on horizontal $F_0$. Nevertheless, the average values of $F_0$ showed a tendency to increase with load, opposing the decrease in $V_0$. Seck et al. (1995) found similar results when evaluating the maximal pedal velocity and the maximal torque for different braking torques during a single all-out exercise on a cycle ergometer.

Regarding the effectiveness, in our study the ES between the unloaded condition and 40% BM (0.85) for $RF_{max}$ was greater than between the unloaded condition and 20% BM (0.57). This is in accordance with studies defending the use of heavier loads because lighter loads will not provide sufficient stimulus to develop sprint performance (Lockie et al., 2003; Kawamori et al., 2014a; Cottle et al., 2014). Furthermore, the *RF-V* relationship for the entire acceleration phase presented in

Figure 4 shows that the effectiveness is greater for heavier loads in the beginning of the acceleration phase until a point in speed where this difference between conditions seems to be reduced. This indicates that using weighted sled towing may be an effective method for sprinters to develop their speed by improving their technique of orienting the force application in a more horizontal direction, in the beginning of the acceleration phase. Indeed, the *F-V* relationship presented in this study (Figure 3) shows that for higher speeds the horizontal force production during the loaded conditions is lower than for the unloaded condition.

When comparing the ability to limit the decrease in *RF* during the acceleration phase ($D_{RF}$) between the sprinting conditions, a significant difference was found between 30% or 40% BM and the unloaded condition. Athletes reduced more their effectiveness of applying force onto the ground in a horizontal direction during sprinting towing a sled with the heavier loads. To our knowledge, this computation had not been compared between different sled towing conditions in sprint running. Morin et al. (2012) investigated the mechanical determinants of 100 m sprinting and found a significant correlation between the $D_{RF}$ index and sprint performance. Possibly, with heavier loads than the ones used in this study the $D_{RF}$ index may be even steeper. This index may be a good representative of the technical ability of a sprinter during the entire acceleration phase and therefore it may be an interesting parameter for the evaluation of the effect of training with resisted sled sprinting. It is possible that after training with a determined sled load the sprinter will be able to limit more the decrease in *RF* and improve his performance by orienting better the application of force in a forward direction during a greater proportion of the acceleration phase. It was not possible to test this hypothesis in the present study, however, it would be an interesting investigation for future studies.

Resisted sled sprinting with the loads used in this study did not caused any difference in $P_{max}$ compared with the unloaded condition. Similar results were found in cycling studies (Seck et al., 1995; Linossier et al., 1996) and treadmill sprinting (Morin et al., 2010). Linossier et al. (1996) investigated $P_{max}$ during a maximal sprint on a friction-loaded cycle ergometer with different braking forces and found that $P_{max}$ was independent of the braking forces. According to Seck et al. (1995), $P_{max}$ can be determined with low and high loads only if the subject exerts a maximal effort and this result is not contrary to isolated muscle experiments since $P_{max}$ is produced when optimal speed is attained. Therefore, if a subject is performing a maximal sprint with different sled towing loads it is possible to observe similar $P_{max}$ during the acceleration phase whenever the best combination of force production and velocity is attained. In contrast with $P_{max}$, our results showed that power at the end of the acceleration phase ($P_{ea}$) increased significantly with the increasing load. Linossier at al. (1996) in their study with cycling found that to reach a maximal velocity more work was performed when the braking forces were greater. The maximal mean power output was attained with heavier loads and this parameter allowed the determination of an optimal braking force for cycling. Furthermore, force friction is increased with heavier loads and the coefficient of friction is related to sprinting velocity, reaching a peak until around 5 $m.s^{-1}$ (Cross MR, unpublished observation). Hence, it is possible that the athletes in the present study were experiencing greater resistance as they approached their maximal velocity sprinting with heavier sled towing loads and were thus performing more work which resulted in the observed higher power output at the end of the acceleration phase. Similarly to cycling studies this parameter is useful in determining an optimal load for resisted sled sprinting, i.e. the load that will elicit the highest power.

This study has some limitations that have to be addressed. The sample evaluated was a bit heterogeneous since men and women were recruited and athletes had different sprint specialties (5 were competing in 400 m events). However, all of them had similar training and were used to train all sprinting distances. Moreover, we acknowledge the fact that prescribing a sled load based on % BM does not consider any possible variation in individual strength among the athletes. However, prescribing a load based on speed reduction makes the comparison with other studies very difficult since different sprinting distances were used to measure speed (Petrakos et al., 2016). During the period in which this study was conducted there was not a more appropriate validated method for prescribing individually the sled load. Furthermore, we believe the behaviour of the *F-V* and *P-V* relationships when comparing different sled loads in this study was not affected by the method used, since it was in agreement with other studies evaluating these parameters.

## Perspectives

This study showed that effectiveness increases with load which indicates that heavier loads cause the athlete to direct his application of force more horizontally. This is an important information for coaches aiming to use the sled towing method to train their athletes. Furthermore, sprinting towing a sled with heavier loads reduces more the effectiveness throughout the acceleration. This could be a good marker to analyse the effect of training and decide when a new load should be applied. It is possible that after an adaptation with a sled load resulting from training the sprinter will be able to limit more the decrease in effectiveness and this could indicate that a new load can be applied to allow further adaptation. Future studies should investigate in track sprinters the effect of training on effectiveness and the ability to limit its reduction during the acceleration. Another message of this study is that $P_{ea}$ increased with load. This parameter may be used to indicate an optimal training load helping a sprinter to exert greater effort during the acceleration to improve his performance.

## Acknowledgements

We would like to thank all the athletes who volunteered to participate in this study as well as their coaches for their cooperation and support. A special thanks also goes to Professor Jean-Benoit Morin (from University of Nice Sophia Antipolis) for his valuable advice during this study and the students and colleagues who helped in any way to make possible the realization of this study. This work was supported by the National Council for Scientific and Technological Development (CNPq) – Brazil, Grant number 203182/2014-6. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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## 5. ARTIGO II

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### Sprint Acceleration Mechanics in Master Athletes

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## ABSTRACT

**Purpose.** The best sprint performances are usually reached between the ages of 20 and 30; however even in well-trained individuals, performance continues to decrease with age. While this inevitable decrease in performance has been related to reductions in muscular force, velocity and power capabilities, these measures have not been assessed in the specific context of sprinting. The aim of this study was to investigate the mechanical outputs of sprinting acceleration among Masters sprinters to better understand the mechanical underpinnings of the age-related decrease in sprint performance. **Methods.** The study took place during an international Masters competition, with testing performed at the end of the warm-up for official sprint races. Horizontal ground reaction force, velocity, mechanical power outputs and mechanical effectiveness of force application were measured during a 30-m sprint acceleration in twenty-seven male sprinters (39 to 96 yrs). Data were presented in the form of age-related changes and compared to elite young sprinters data. **Results.** Maximal force, velocity and power outputs decreased linearly with age (all $r>0.84$; $P<0.001$), at a rate of ~1% per year. Maximal power of the oldest subject tested was about one ninth of that of younger world-class sprinters (3.57 vs. 32.1 $W \cdot kg^{-1}$). While the maximal effectiveness of horizontal force application also decreased with age, its decrease with increasing velocity within the sprint acceleration was not age-dependent.

**Conclusions.** In addition to lower neuromuscular force, velocity and power outputs, Master sprinters had a comparatively lower effectiveness of force application, especially at the beginning of the sprint.

**Key Words:** ageing, performance, power, running, force, effectiveness

## INTRODUCTION

Sport participation is an important component of healthy ageing. While strength (e.g. weightlifting) and endurance (e.g. long-distance running) activities are often recommended and studied in healthy elderly individuals (31), sprint running is also endorsed for practice and competitions. Over the past years, there has been an increasing number of participants to Masters-level competitions (11), including sprint running events like the 100-m. Since training and competing for sprint running requires strength, power, coordination, flexibility and many other fitness components, sprint running has recently been considered an equivalent model (compared to endurance) for maintaining recommended levels of physical activity with aging (20). For instance, it has been shown that older trained sprinters (70 yrs) possess very similar maximal isometric knee extensor force and rate of force development capabilities compared to younger (40 yr) yet sedentary individuals (15).

Similarly to distance running, a systematic decrease in performance has been observed in sprint running with ageing (4, 34). Interestingly, decreases in performance during both long- and short-distance events have been reported before the increase in participants over the modern training and competing era (22), and the likely associated increase in overall practice in this population. Research has therefore been conducted to identify the mechanisms underlying this age-related decrease in sprint performance (2), which also describes the limits of the human capabilities for legged locomotion acceleration and speed.

The rate of decline in sprint performance over the age categories (from the peak level at 20-25 yrs until the 70s) is consistent among studies at ~0.6 to 0.8 % per year (4, 22, 34, 35). Slower sprint speed is consistently associated with decreased step length and step rate (13, 16, 17). Interestingly, the reported minor changes in step rate are a result from opposite changes in the sub-components of step rate: substantial increases in contact time have been observed, along with almost identical decreases in aerial time (13, 16, 17). Reduced velocity due to a decrease in step length suggests a substantial decrease in ground impulse production capability with ageing in sprinters, despite longer time of force application onto the ground (17, 19).

This decrease in lower limb ground impulse capability is likely resulting from one or more of the following neuromuscular factors. A decline in lower limb maximal strength has been observed in general (8, 15, 39) and sprint-trained populations (15). The rate of force development during maximal voluntary actions (isometric contractions, lower limb extension or vertical jumping) is also impaired in both types of populations (1, 9, 15). Finally, mechanical power, which is equivalent to the product of force and velocity outputs, markedly declines with age in both sprint-trained and sedentary subjects, when assessed with vertical jumps (9, 21) or lower limb multiple joint extensions (1).

The main drawback of studies profiling the age-related decline in sprint performance is that neuromuscular capabilities are investigated during non-specific actions: single-joint isometric or isokinetic contractions (e.g. (15, 32), and ballistic multiple-joint lower limb extensions (i.e. horizontal or vertical push-offs (1, 9, 21). To our knowledge, only few studies have investigated the specific sprint motion mechanics in a functional and direct manner in Master sprinters (i.e. using sprint motion during competition as a testing modality). Hamilton (13) and Korhonen et al. (16) studied sprint kinematics (step length/rate and contact/aerial times) using video analyses during official sprint races (international Masters track and field championships) in a group of athletes ranging from 30 to 90 yrs old. Although this approach provides a detailed description of the changes in sprint spatio-temporal variables and their relationship with ageing, it does not offer understanding of the causes of sprint motion, i.e. the ground reaction forces (GRF) acting on athlete's center of mass. Thus, kinetic measurements could provide valuable additional insights.

To our knowledge, only Korhonen et al. (17, 18) studied GRFs during the maximal (i.e. constant) speed phase of a 60-m sprint in Master sprinters (40 to 82 yrs old). The authors found an overall decrease in the magnitude of GRF development in both braking and propulsive phases (-0.9 and 0.8 % per year, respectively), and a more vertically-oriented angle of push with age. Despite the new insights produced by these two studies, their main limitations were that (i) only a few steps were measured per trial (9-m track-embedded force plates), and (ii) the measurements were taken during the top-speed phase. These limitations are important as maximal horizontal GRF and power outputs occur during the beginning of the acceleration (29, 33).

Recently, Samozino et al. (36) proposed a valid and simple method to compute force and power during a sprint acceleration based on speed-time measurements. This method is easy to implement in field conditions and only requires subjects to perform a maximal acceleration up to their top speed from a standing start. The interest of this method is that it allows a more detailed understanding of the mechanical outputs (force, velocity, power, effectiveness of ground force application) that determine sprint performance compared to standard time or speed measurements (27). Since a short (~30 m) maximal acceleration is an effort all sprinters traditionally perform at the end of their warm-up in competition, we could plausibly measure Masters sprinters during an international competition to assess the mechanical features of sprint performance in this specific population.

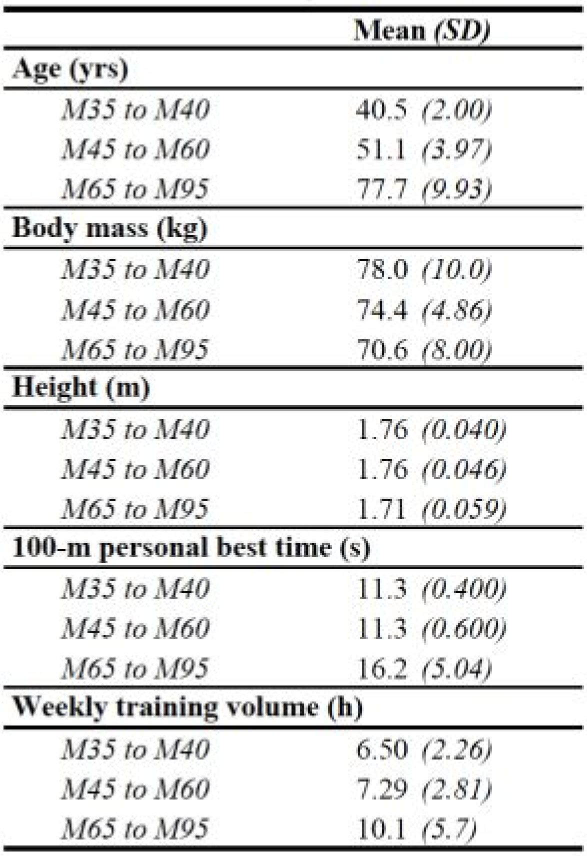
The aim of this study was to investigate the sprint acceleration mechanical outputs of trained Masters sprinters (including world-class athletes). Our purpose was to better understand the mechanical underpinnings of the decrease in sprint performance associated with age, and to compare the mechanical determinants of sprint performance in this population to younger elite athletes (23, 24, 33, 38).

## METHODS

### Subjects and experimental protocol

Twenty-seven male subjects volunteered for the study and gave their written informed consent (detailed characteristics are listed in Table 1). All subjects were trained sprinters, with several having competed in the 2015 World Master Athletics Outdoor Championship in Lyon, France. Subjects' age ranged from 39 to 96 yrs, and our data were split into three age sub-categories for presentation clarity: M35 to M40 (n = 6); M45 to M60 (n = 14) and M65 to M95 (n = 7), where M stands for male athletes. These were the official categories of the competition with M40 including subjects aged up to 44, and M60 subjects aged up to 64. Note that the "M65 to M95" category included one subject, aged 96 years, who was the official world record holder on the indoor 200-m in the M95 age category (source: http://www.world-masters-athletics.org).

**Table 1.** Main anthropometric and training characteristics of the subjects.



| | Mean *(SD)* |
|---|---|
| **Age (yrs)** | |
| *M35 to M40* | 40.5 *(2.00)* |
| *M45 to M60* | 51.1 *(3.97)* |
| *M65 to M95* | 77.7 *(9.93)* |
| **Body mass (kg)** | |
| *M35 to M40* | 78.0 *(10.0)* |
| *M45 to M60* | 74.4 *(4.86)* |
| *M65 to M95* | 70.6 *(8.00)* |
| **Height (m)** | |
| *M35 to M40* | 1.76 *(0.040)* |
| *M45 to M60* | 1.76 *(0.046)* |
| *M65 to M95* | 1.71 *(0.059)* |
| **100-m personal best time (s)** | |
| *M35 to M40* | 11.3 *(0.400)* |
| *M45 to M60* | 11.3 *(0.600)* |
| *M65 to M95* | 16.2 *(5.04)* |
| **Weekly training volume (h)** | |
| *M35 to M40* | 6.50 *(2.26)* |
| *M45 to M60* | 7.29 *(2.81)* |
| *M65 to M95* | 10.1 *(5.7)* |

The study was conducted during the European Master Games in Nice, France (http://emg-nice2015.fr) on October 3 and 4, 2015. It was approved by the institutional ethics review board of the Faculty of Sport Sciences, and conducted according to the Declaration of Helsinki II. Although female sprinters were recruited and tested, the total number of athletes and their age categories distribution prevented us from presenting the data in this study. As a result, only male subjects' data were used for the analysis in this study.

This cross-sectional study took place on the warm-up synthetic track (Tartan™). No external factor (i.e. temperature, wind, time of day) substantially differed between subjects during their respective testing. After complete explanation of the protocol on their arrival at the competition site, subjects were asked to perform their personal sprint warm-up routine, and the testing was scheduled, for each subject, in the 10 minutes preceding their access to the call room before sprint events (100, 200 or 400-m). Following their warm-up routine, subjects' body mass was measured before performing a maximal 30-m acceleration from a standing start, wearing competition clothes and shoes. Running speed data were sampled (47 Hz) using a radar device (Stalker ATS Pro II, Applied Concepts, Plano, TX, USA) placed at a height of 1 m off the ground and ~5 m behind the starting line. Due to the competition context, 6 subjects out of 27 were allowed to do the testing after their 100-m race, and asked to perform this testing at least 20 min after the race, and after a shortened warm-up procedure. Given the short duration of a 100-m sprint, we can reasonably assume that testing these athletes after the race did not significantly alter their sprint performance or mechanics.

## Mechanical variables

The computation method used was recently presented (for full details, see (36)), and is based on a macroscopic inverse dynamics analysis of the center of mass motion. This method has been recently shown valid and reliable in comparison to ground-embedded force plates measurements, and all the mechanical outputs detailed below (force, power, effectiveness) were calculated from the measurement of subjects' body height, mass, and running speed during acceleration (36). Briefly, during a maximal acceleration, raw velocity-time data measured with the radar device are very well fitted by an exponential function (Figure 1, for details on this exponential fitting see (7, 12, 26, 36)):

$$v(t) = v_{\max}(1 - e^{-t/\tau}) \qquad (1)$$

with $v_{max}$ as the maximal velocity reached at the end of the acceleration and $\tau$ the acceleration time constant (Figure 1). Instantaneous velocity was then derived to obtain the horizontal acceleration $a_H$. Then, applying the fundamental principles of dynamics in the horizontal direction, the net horizontal antero-posterior GRF ($F_H$) applied to the body center of mass can be modeled over time as:

$$F_H(t) = ma_H(t) + F_{air}(t) \qquad (2)$$

with $m$ as the athlete's body mass (in kg) and $F_{air}(t)$ as the estimated aerodynamic friction force to overcome during sprint running (for details, see (3, 36)). The equivalent of power output in the horizontal direction ($P_H$) was computed as the product of instantaneous $F_H$ and $v$.

Individual force-velocity and power-velocity relationships were determined from $F_H$, $P_H$ and $v_H$ values using least-square linear and second-order polynomial regressions, respectively (14, 23, 28)). Force-velocity relationships were then extrapolated to obtain theoretical maximal force ($F_0$) and velocity ($V_0$) capabilities as the intercepts of the force-velocity curve with the force and velocity axis, respectively. Maximal power output $P_{max}$ (expressed in W per kg of body mass) was computed via a validated equation (36, 40) as follows:

$$P_{\max} = \frac{F_0 V_0}{4} \tag{3}$$

Finally, the mechanical effectiveness of force application was quantified over each step by the ratio ($RF$ in %) of $F_H$ to the corresponding resultant GRF ($F_{RES}$), and over the entire acceleration phase by the slope of the linear decrease in $RF$ when velocity increases ($D_{RF}$) (24):

$$RF = \frac{F_H}{F_{RES}}.100 = \frac{F_H}{\sqrt{F_H^2 + F_V^2}} \tag{4}$$

with $F_V$ as the mean net vertical GRF applied to the body center of mass over each complete step, which can be modeled over time as equal to body weight (see details in (6, 36)). In accordance with previous research (24, 33, 36), $RF$ and $D_{RF}$ were computed from $F_H$ and $F_V$ values modeled for $t > 0.3$ s. The theoretical maximal value of effectiveness ($RF_0$) was computed as the y-intercept of the $RF$-$v$ linear relationship (Figure 2). The maximal value of $RF$ actually reached at the beginning of the acceleration was termed $RF_{max}$.

## Data analysis and statistics

Descriptive statistics are presented as mean values ± SD. Normal distribution of the data was confirmed by the Shapiro-Wilk normality test. Changes in the mechanical variables with age were mainly described using Pearson's correlations computed between experimental variables and age, and the rate of change in these variables with age. To compare the Masters athlete's data with those of younger elite athletes, we reported the results of a recent study of Rabita et al. (33) for their elite group (n = 4; mean age of 25, 100-m personal best time of ranging from 9.95 to 10.29 s at the time of the study). For clarity, data for these four athletes will be presented under the name of "young elite". Furthermore, since these data were obtained during sprint accelerations with starting-blocks (compared to the standing start used in the current study), they will be used as complementary information, and not included in the regression analyses.

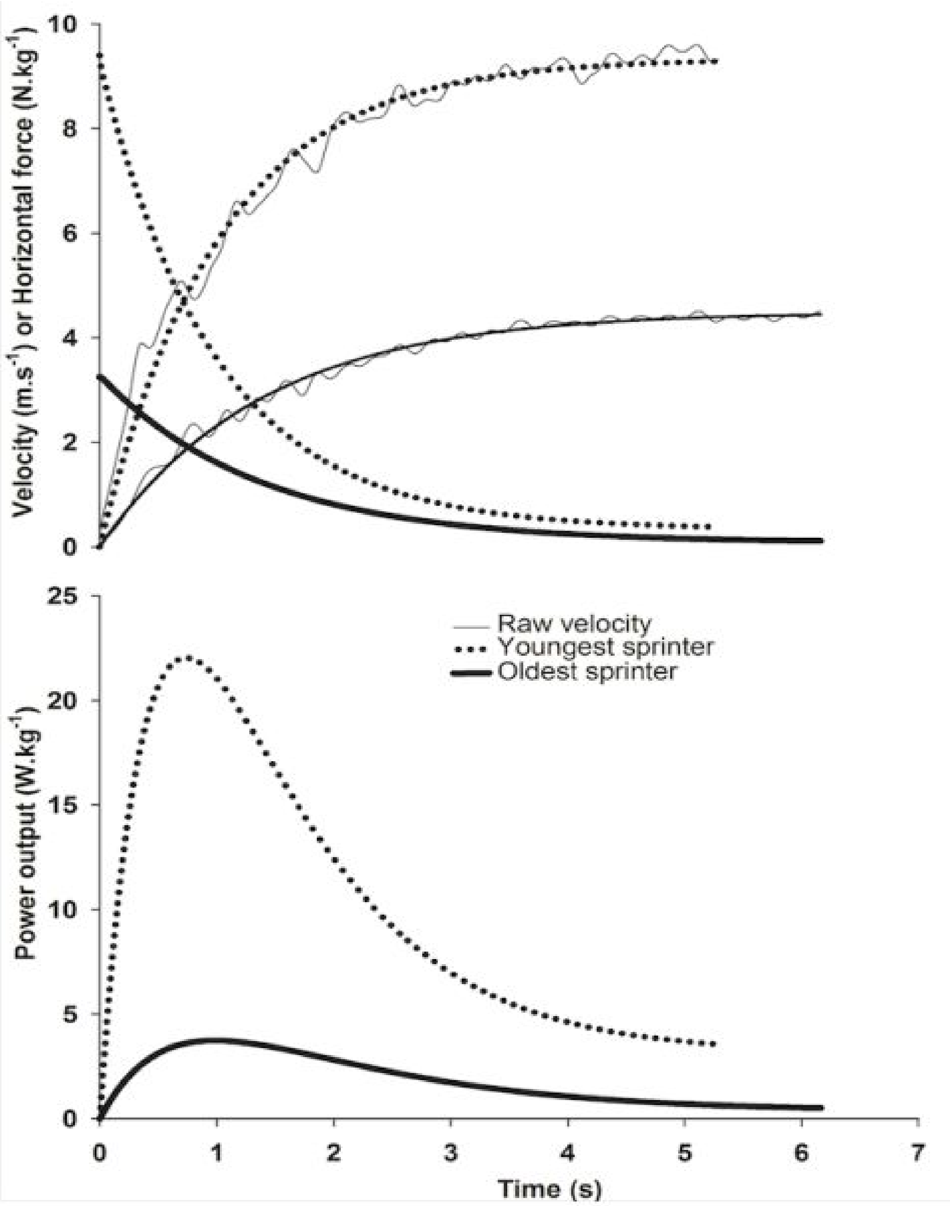


**Figure 1.** Upper panel: running velocity and horizontal force outputs as a function of time during a sprint acceleration. Lower panel: mechanical power output as a function of time during the acceleration. Black and dotted lines are data from the oldest (96 yrs) and youngest athlete (39 yrs) tested, respectively.

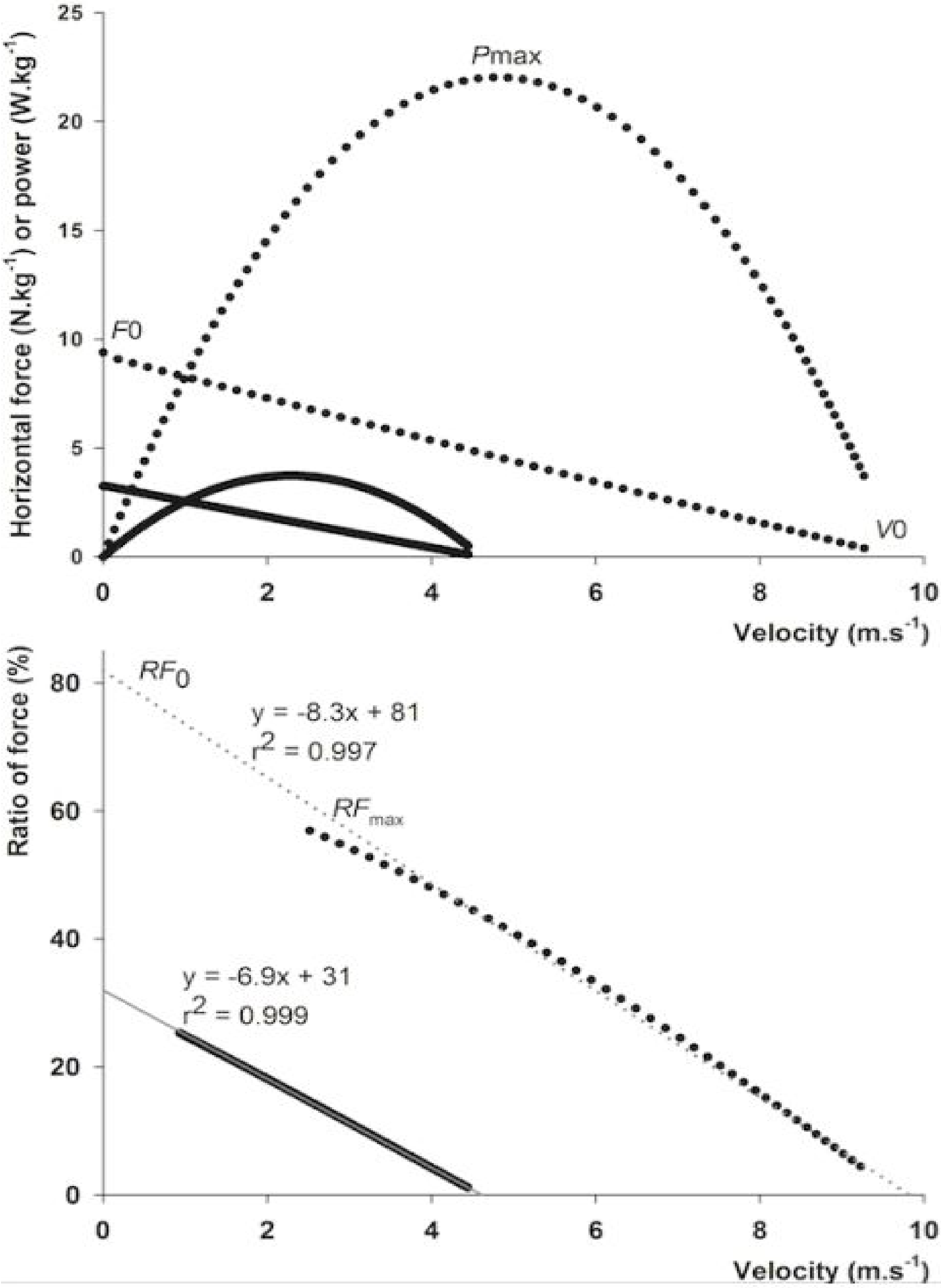
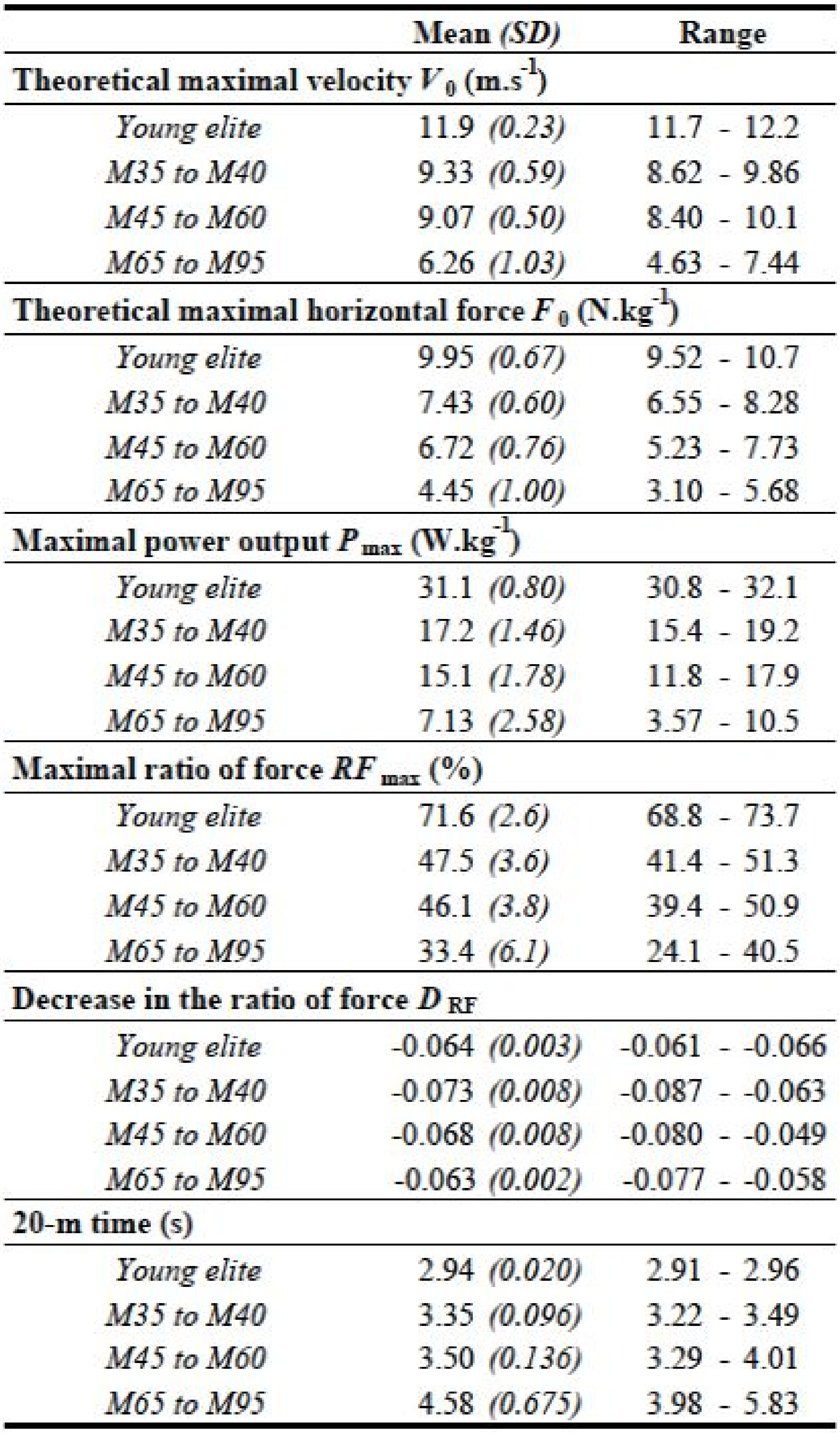


**Figure 2.** Upper panel: force- and power-velocity relationships during the sprint acceleration. $F_0$: maximal theoretical force output in the horizontal direction; $V_0$: maximal theoretical running velocity; $P_{max}$: maximal mechanical power output. Lower panel: linear decrease in the ratio of force as a function of running velocity. $RF_0$: maximal theoretical value of the ratio of force. $RF_{max}$: maximal value of the ratio of force actually reached (first step). The $D_{RF}$ index is the slope of the decrease in $RF$ with velocity (-0.083 and -0.069 in this figure). Black and dotted lines are data from the oldest (96 yrs) and youngest athlete (39 yrs) tested, respectively.

## RESULTS

The main performance and mechanical variables are shown in Table 2.

**Table 2.** Mechanical variables of sprint acceleration and performance for each age group. Data for young elite sprinters are from Rabita et al. (2015).



| | Mean *(SD)* | Range |
|---|---|---|
| **Theoretical maximal velocity $V_0$ (m.s$^{-1}$)** | | |
| *Young elite* | 11.9 *(0.23)* | 11.7 - 12.2 |
| *M35 to M40* | 9.33 *(0.59)* | 8.62 - 9.86 |
| *M45 to M60* | 9.07 *(0.50)* | 8.40 - 10.1 |
| *M65 to M95* | 6.26 *(1.03)* | 4.63 - 7.44 |
| **Theoretical maximal horizontal force $F_0$ (N.kg$^{-1}$)** | | |
| *Young elite* | 9.95 *(0.67)* | 9.52 - 10.7 |
| *M35 to M40* | 7.43 *(0.60)* | 6.55 - 8.28 |
| *M45 to M60* | 6.72 *(0.76)* | 5.23 - 7.73 |
| *M65 to M95* | 4.45 *(1.00)* | 3.10 - 5.68 |
| **Maximal power output $P_{max}$ (W.kg$^{-1}$)** | | |
| *Young elite* | 31.1 *(0.80)* | 30.8 - 32.1 |
| *M35 to M40* | 17.2 *(1.46)* | 15.4 - 19.2 |
| *M45 to M60* | 15.1 *(1.78)* | 11.8 - 17.9 |
| *M65 to M95* | 7.13 *(2.58)* | 3.57 - 10.5 |
| **Maximal ratio of force $RF_{max}$ (%)** | | |
| *Young elite* | 71.6 *(2.6)* | 68.8 - 73.7 |
| *M35 to M40* | 47.5 *(3.6)* | 41.4 - 51.3 |
| *M45 to M60* | 46.1 *(3.8)* | 39.4 - 50.9 |
| *M65 to M95* | 33.4 *(6.1)* | 24.1 - 40.5 |
| **Decrease in the ratio of force $D_{RF}$** | | |
| *Young elite* | -0.064 *(0.003)* | -0.061 - -0.066 |
| *M35 to M40* | -0.073 *(0.008)* | -0.087 - -0.063 |
| *M45 to M60* | -0.068 *(0.008)* | -0.080 - -0.049 |
| *M65 to M95* | -0.063 *(0.002)* | -0.077 - -0.058 |
| **20-m time (s)** | | |
| *Young elite* | 2.94 *(0.020)* | 2.91 - 2.96 |
| *M35 to M40* | 3.35 *(0.096)* | 3.22 - 3.49 |
| *M45 to M60* | 3.50 *(0.136)* | 3.29 - 4.01 |
| *M65 to M95* | 4.58 *(0.675)* | 3.98 - 5.83 |

The decrease in sprint acceleration performance with age was related to a decrease in $P_{max}$, and in both the maximal force and velocity components (Figure 3). Furthermore, the effectiveness of force application at the very beginning of the acceleration ($RF_{max}$) decreased with age, and was less than half (33.4% on average) in the older sprinters tested compared to their young elite counterparts (71.6%). The only mechanical variable that did not change substantially with age was the decrease in the ratio of force with increasing velocity ($D_{RF}$), i.e. the ability to limit the loss in effectiveness over the acceleration. The two latter results are illustrated in Figure 2: the *RF*-velocity relationships of the youngest and oldest sprinters tested have a very similar rate of decrease, yet the y-intercept of this relationship ($RF_{max}$, that characterizes the effectiveness of forward GRF application at the first steps) is much lower in the older athlete.

The above-mentioned age related changes in sprint acceleration performance and mechanics with age were well described by linear regressions (all significant with r>0.84, except for $D_{RF}$, Figure 3 and 4).

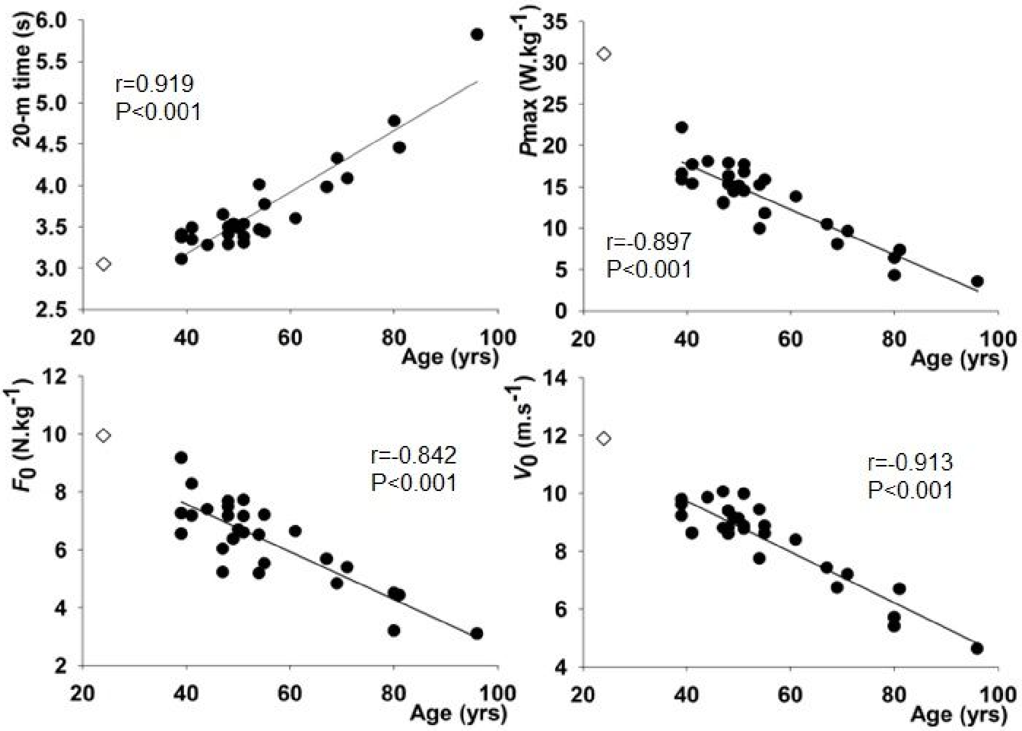


**Figure 3.** Correlations illustrating the changes in sprint acceleration performance and mechanical outputs with age. Black dots represent the subjects of the present study, white diamonds represent the average values of the four young elite sprinters in Rabita et al. (2015), for comparison. The linear equations are computed on Masters subjects' data only (black dots), and are all significant (all $P<0.001$).

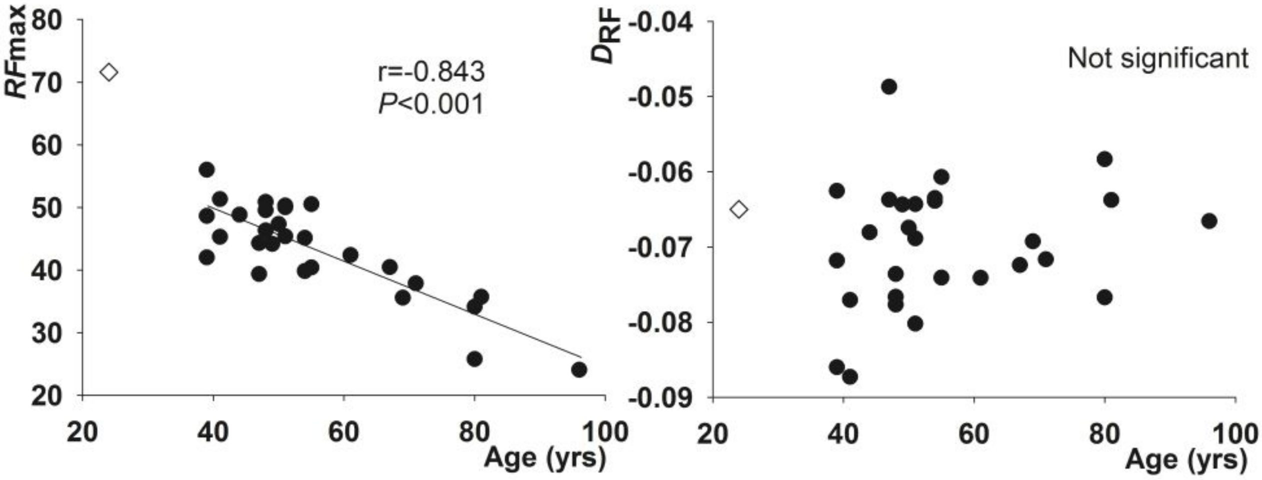


**Figure 4.** Correlations illustrating the changes in the effectiveness of ground force application with age (left: maximal ratio of force; right: decrease in the ratio of force with increasing velocity). Black dots represent the subjects of the present study, white diamonds represent the average values of the four young elite sprinters in Rabita et al. (2015) for comparison. The linear equations are computed on Masters subjects data only (black dots), and are significant ($P$<0.001) for $RF_{\mathrm{max}}$ only.

The average rate of decrease in 20-m sprinting acceleration performance for the present group (~60-yrs range) was equal to ~1.10% per year. This was associated with a decrease in $P_{max}$ of ~1.60% per year. The two mechanical determinants of $P_{max}$ showed similar rates of decrease around 1% per year: 1.10% per year for $F_0$ and 0.94% per year for $V_0$ . The rate of decrease in $RF_{max}$ was 0.88% per year. As shown in Figure 4, $D_{RF}$ did not change with age. Note that these rates of decrease were close when adding the elite young data to the regression analysis.

## DISCUSSION

This study aimed at better understanding the changes in sprint acceleration mechanics that are associated with the sprint performance decline in trained Master athletes. Similar to previous studies (4, 34, 35), sprint performance (20-m time, maximal running speed) decreased linearly with age in the population of competitive sprinters tested (39 to 96 years old, 1.10% decrease per year on average). This decline in performance was associated with a linear decline in estimated maximal power output. Figure 1 and 2 show for instance the individual data from the oldest and youngest sprinters tested, with $P_{max}$ markedly lower in the oldest sprinter compared to the youngest athlete tested (3.57 $W.kg^{-1}$ versus 22.1 $W.kg^{-1}$). The main novel findings of this study are that (i) the estimated maximal force and velocity components of the mechanical power output of sprint acceleration showed similar rates of decline (about 1% per year) and (ii) in computed effectiveness of force application at the beginning of the sprint decreased substantially with age (significant linear decline of 0.88% per year in RF max ), whereas the ability to limit the decrease in effectiveness with increasing velocity was not (unchanged $D_{RF}$); as shown in Figure 2 for the two typical subjects mentioned above.

The main advantages of using the field method to compute the entire force-velocity-power estimate of sprinters (27, 36), as we did during this official Masters competition is that it provides a more detailed understanding of the mechanical features of the decline in performance with age. Contrary to isometric maximal voluntary force production (e.g. (15, 32)) or jump tests (e.g. (9, 21)), mechanical characteristics were estimated during the sprinting task, leading specific and functional insights into the physical determinants of sprint performance in trained Master athletes. It also allows computation of a more technical feature of sprint performance that is the effectiveness of force application, that is characterized by (i) the ability to orient the ground push forward at the very beginning of the sprint ($RF_{max}$) and (ii) the ability to keep doing so throughout the acceleration ($D_{RF}$) despite the increase in velocity and the inevitable drop in effectiveness (more vertical orientation step after step). These two components of sprint acceleration mechanics have been shown to directly relate to performance from non-specialists to world-class athletes (23, 24, 33). To our knowledge, such computations had not been performed in Masters sprinters, since sprint kinetics had only been measured for a few steps on a force plate (17, 18) during the maximal speed phase of a 60-m sprint. Moreover, these findings extend the previous understanding of mechanical output generation during running at constant, submaximal speed (5). In this study (5), the authors observed a clearly different pattern with quasi-exclusively positive work generation in older men, with a greater horizontal force output as a fraction of resultant force compared to their younger counterparts. Contrastingly, our results show that in accelerated running up to maximal speed, master athletes show an overall lower ratio of force.

The decline in sprint performance observed here has been reported previously, both with regards to best performances by age category (4, 22, 34, 35) and from direct measurements during competitions (e.g. 100-m races) (13, 16). Previous authors attributed this decrease in sprint performance to declining muscular power capabilities, which is consistent with the decrease in $P_{max}$ observed in the present study (Figure 3). Interestingly, this decrease in power output was determined by equivalent decreases in $F_0$ and $V_0$, which supports the notion that maximal force and maximal velocity capabilities of the neuromuscular system are involved in the overall decrease in sprint performance with age. This also shows, in a sprint-specific testing context, that previously reported loss in maximal muscular force and shortening contraction velocity and power output in older subjects (1, 8, 10, 15, 30, 32, 37, 39) transfers to the specific task of sprint running. In addition, it indicates that although trained Master athletes show values that are similar to untrained younger subjects (15), this decline in strength and power is an inevitable consequence of the ageing process. Training and competitive practice may not prevent these changes occurring, but it may attenuate it (2, 20).

One unexpected result of the present study was that the decrease in force application effectiveness with increasing velocity during sprint acceleration (the $D_{RF}$ index) did not change with age (Figure 4), contrary to all other estimated mechanical variables. However, we found significant decreases in the level of initial effectiveness of ground force application ($RF_{max}$). Thus, when considering both the effectiveness at the very beginning of the sprint acceleration ($RF_{max}$) and how this effectiveness decreases as velocity increases ($D_{RF}$), the difference in sprint performance between younger and older subjects might be explained by the fact that older subjects “lose” effectiveness at a comparable rate, but their initial mechanical effectiveness is much lower. This is well illustrated by the typical example in Figure 2 (lower panel): the slope of the *RF*-velocity relationship is not substantially different between the older and the younger subjects compared, but the $RF_{max}$ of the older sprinter is about half of that of the younger one (thus, the entire RF-velocity relationship is less efficient in the older sprinter).

This means that older sprinters are not able to crouch and orient their ground reaction force horizontally as well as their younger counterparts, perhaps due to their overall lower limb strength or balance capabilities (i.e. a fear of falling in case of forward imbalance). Anecdotally, this was the reason given by the oldest subjects of the study for not using starting-blocks in competition races.

The importance of both $RF_{max}$ and $D_{RF}$ variables for sprint acceleration performance has been discussed in elite young sprinters (23, 24, 33). Recently, Morin et al. (25) experimentally showed a relationship between hip extensor muscular force and activity and the ability to produce horizontal GRF during sprinting. It is possible, as discussed by Kulmala et al. (19) that a specific weakness in hip extensors in Master athletes is associated with this decrease in the ability to orient the ground push horizontally, especially at the beginning of the acceleration. In summary, these results show that in addition to decreasing power, force and velocity outputs with ageing, older sprinters exhibit lower technical ability to apply force effectively. Thus, the decrease in sprint performance with ageing results from both a decrease in the magnitude of force output and altered ground force application effectiveness.

This study has limitations that should be addressed. First, our integrative macroscopic approach considers a net force output, and therefore does not allow for braking and propulsive phase distinction, as previous authors have (16, 17). However, although based on computation and estimated outputs, the current approach does allow for an overall understanding of the entire acceleration mechanics' "big picture". Except for a recent elite sprinters database analysis (38), no experimental data has been published to our knowledge on the mechanical outputs of sprinters in a competition context. Second, although our measurements were performed at the end of a warm-up, we do think the data presented here gives a good estimate of the specific force-velocity-power spectrum of Master sprinters and of their technical effectiveness of force application. This might pave the way for applications in training, especially in an attempt to limit the decrease in initial effectiveness ($RF_{max}$) in order to maintain an efficient propulsion throughout the acceleration. Finally, the study was done during an official international competition (European Master Games) open to all participants (no qualifying minimal performances), which led to a relatively non-homogeneous sample with regards to performance level than e.g. the World Master Athletics outdoor championships. Although several subjects tested in the present study participated to both events in 2015, further studies should confirm the present results during top-level Masters competitions, including female athletes. That being said, the elite young sprinters data shown in Figures 3 and 4 are well aligned with the Masters data, which tends to support that the linear regressions studied may apply to the entire age span, from top-level performance in the mid 20's to top-level performance near 100 years of age.

In conclusion, this study on Masters sprinters acceleration mechanics shows that the decrease in sprint performance results from equivalent decreases in estimated maximal power, force and velocity capabilities of the neuromuscular system. These capabilities decreased linearly with age, at rates close to 1% per year over the ~70 years span studied. Finally, the computed effectiveness of ground force application was substantially lower in older sprinters compared to their younger counterparts at the beginning of the sprint. Despite a similar maintenance of mechanical effectiveness with increasing velocity during the acceleration, this much lower initial effectiveness offers further insight into the lower acceleration performance in Master sprinters, and may be a key target for training intervention in this population.

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## 6. ANÁLISE INTEGRATIVA DO EFEITO DA CARGA E DA IDADE

Neste tópico, proponho analisar a magnitude do efeito da carga e da idade sobre os parâmetros do modelo teórico apresentado na introdução geral da presente tese, para compreender a influência que cada efeito exerce sobre o modelo. Quais parâmetros são alterados para cada efeito e o quanto eles são alterados, podem ser informações importantes para os treinadores que pretendem elaborar um plano de treino para atletas master ou um plano de treino que inclui a utilização do trenó com diferentes cargas. A Tabela 1 apresenta a diferença percentual que pode ser observada entre as situações extremas do efeito da carga e do efeito da idade, ou seja, a diferença entre a situação sem carga e a situação em que o atleta corre com o trenó com peso correspondente a 40% da massa corporal, para cada parâmetro avaliado, e a diferença entre as categorias mais jovens do Campeonato master e as categorias de idade mais avançada, para os mesmos parâmetros avaliados.

**Tabela 1.** Diferença percentual entre a situação sem carga e a carga mais pesada utilizada no estudo do efeito da carga (40% da massa corporal), e diferença percentual entre o valor médio das categorias mais jovens e o das categorias de idade mais avançada, em atletas master, avaliadas no estudo do efeito da idade, para cada parâmetro. Valores negativos indicam redução.

| | **Efeito da Carga (0% vs 40%)** | **Efeito da Idade (M35 a M40 vs M65 a M95)** |
|---|---|---|
| **V0** | -17,8% | -32,9% |
| **F0** | 12,9% | -40,1% |
| **Pmax** | -7,3% | -58,5% |
| **$RF_{max}$** | 12,2% | -29,7% |
| **$D_{RF}$** | -22,6% | 13,7% |
| **Tempo** | 31,6% | 26,9% |

Para a maior parte dos parâmetros avaliados em ambos os estudos, o efeito da idade se sobressai em comparação com o efeito da carga, por provocar maior alteração nos parâmetros do modelo teórico apresentado. As variáveis $V_0$, $F_0$, $P_{max}$ e $RF_{max}$ apresentaram um maior percentual para o efeito da idade do que para o efeito da carga, indicando que para a amplitude de idade avaliada no artigo II esses parâmetros se alteram consideravelmente entre as categorias que incluem atletas master mais novos e aquelas que incluem atletas master de idade mais avançada. Esta análise sugere que o efeito da idade, com a característica de atrofia muscular com redução de fibras rápidas, redução da velocidade de encurtamento e menor efetividade durante a corrida, influencia mais o modelo teórico do que o efeito da resistência que o trenó oferece com a carga. Deve-se levar em consideração, entretanto, que este maior efeito da idade do que resistência do trenó é dependente das cargas utilizadas na presente tese. É provável que com cargas maiores o percentual do efeito da carga aumente, no entanto, não se sabe qual seria a magnitude desse aumento e se o valor percentual se aproximaria do valor obtido para o efeito da idade.

Em contraste com os parâmetros acima citados, a $D_{RF}$ e o tempo foram mais alterados pelo efeito da carga do que pelo efeito da idade. Para a $D_{RF}$, é possível que esse resultado tenha sido observado devido à menor efetividade máxima que os idosos apresentam no início da corrida de velocidade, o que faz com que o valor não sofra uma redução considerável durante a fase de aceleração. Na situação com cargas, a efetividade aumenta com a adição de cargas no início da corrida e dessa maneira a redução é mais pronunciada no decorrer da aceleração. O maior percentual do tempo de corrida para o efeito da carga, indica o quanto a resistência oferecida pelo trenó altera esse parâmetro de desempenho de corrida, sugerindo o quanto esse método pode ser eficiente para provocar adaptações nos atletas que levem a uma futura redução do tempo de corrida por consequência do treinamento. O tempo de corrida e a $D_{RF}$ foram os parâmetros que mais sofreram alteração com o efeito da carga, e a $P_{max}$ e a $F_0$ foram os parâmetros que mais sofreram alteração com o efeito da idade. Talvez seja interessante combinar esses dois efeitos em uma futura investigação, para analisar de que maneira o modelo é alterado pela corrida realizada com o trenó com diferentes cargas, por atletas master de diferentes idades. O treino com o trenó para atletas master pode ser interessante para a melhora da efetividade durante a fase de aceleração da corrida, no entanto, como esse método parece não alterar consideravelmente a $P_{max}$, embora altere a potência no final da aceleração, é provável que a adição de um outro método específico para treinar a $P_{max}$ em atletas master seja útil para acrescentar uma melhora no desempenho desses atletas. Vale ressaltar que outros efeitos como as diferentes superfícies de corrida (como correr na grama, por exemplo), diferentes tipos de treino e o uso de diferentes equipamentos também podem alterar os parâmetros do modelo teórico apresentado.

# 7. CONSIDERAÇÕES FINAIS

A presente tese teve o objetivo de avaliar parâmetros determinantes das relações força-velocidade e potência-velocidade, assim como a efetividade, sob o efeito da carga e da idade durante toda a fase de aceleração da corrida de velocidade, em atletas velocistas. O artigo I, que apresentou o efeito da carga, conclui que a efetividade aumenta com o aumento da carga no início da aceleração, indicando que esse parâmetro pode ser útil para o treinamento com trenó com cargas mais pesadas do que aquelas recomendadas em pesquisas anteriores. Além disso, a capacidade de manter a efetividade ao longo da fase de aceleração, diminui com o aumento da carga. Talvez esse seja um bom marcador para avaliar o efeito do treino e decidir quando uma nova carga deve ser aplicada. Se por consequência do treino o atleta melhora a manutenção da efetividade durante a fase de aceleração da corrida, a $D_{RF}$ será um bom indicador para que uma nova sobrecarga seja prescrita e uma futura adaptação seja adquirida. Além disso, a maior potência encontrada no final da fase de aceleração com o aumento da carga pode ser útil para a prescrição de uma carga ótima de treino, ou seja, aquela carga que irá provocar a maior produção de potência durante a aceleração.

O artigo II, que investigou o efeito da idade, conclui que a redução no desempenho da corrida de velocidade com o avanço da idade ocorre devido ao declínio da $P_{max}$, da força e da velocidade. Há um declínio de aproximadamente 1% por ano nessas variáveis. Além desses parâmetros, a efetividade foi consideravelmente mais baixa nos atletas com idade mais avançada em comparação com aqueles mais jovens. Sugere-se que os treinadores de atletas master também estejam atentos a esse parâmetro, visto que a orientação para que a aplicação de força ocorra de maneira mais horizontal pode auxiliar atletas a melhorarem a sua efetividade e consequentemente o seu desempenho. O treinamento realizado com o trenó pode ser uma boa estratégia para que os atletas master tenham essa melhora, no entanto, estudos futuros devem testar essa hipótese.

# 8. TRABALHO COMPLEMENTAR REALIZADO DURANTE O DOUTORADO SANDUÍCHE

## ARTIGO III

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### Running Energy Cost and Spring-Mass Behavior in Young Versus Older Trained Athletes

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### ABSTRACT

**Purpose**: The aim of this study was to compare energy cost of running and lower limb spring-mass characteristics and maximal power, between young and older highly trained runners. **Methods:** Twenty highly trained male endurance runners were divided into two groups: young and master athletes. Two testing sessions were used to measure and compare (i) lower limb power during three jumping tests (squat jump (SJ), countermovement jump (CMJ), rebound jump (RJ)) as well as stiffness during the RJ test and running trials (using an OptoJump system, placed on the floor for jumping and on each side of the treadmill belt for running), and (ii) the energy cost of running (using an Oxycon Pro breath-by-breath gas analyzer) at three speeds: 10 km.h$^{-1}$, self-selected speed, and speed corresponding to 90% of the second ventilatory threshold (VT2). **Results:** Energy cost of running was higher in masters than in young athletes at all speeds (10 km.h$^{-1}$: 13.0%; self-selected: 10.8%; 90% VT2: 7.7% on average). Jumping power was lower in masters (SJ: -28.0%; CMJ: -30.5%; RJ: -27.9%) and significantly correlated with energy cost at 10 km.h$^{-1}$ and at self-selected speed (10 km.h$^{-1}$ r = -0.71; -0.70; -0.47; self-selected speed: r = -0.76; -0.74; -0.58, respectively).

RJ stiffness was also lower in masters (-27.8%), although stiffness during running showed no difference between groups. **Conclusions:** A long-lasting running practice seemed to preserve the bouncing mechanism of master athletes, yet their energy cost was higher when compared to younger runners, which might have been associated with a lower muscle power.

**Key Words:** Running Economy, Spring-Mass Model, Ageing, Muscle Power, Master Athletes

## INTRODUCTION

Increasing numbers of older Master or Veteran athletes are regularly training and competing in sport (18, 39) and provide a unique opportunity to better understand the physiological alterations that occur with ageing in active participants. Master athletes are described as people regularly training (e.g. in endurance in this study) to compete and maintain their physical performance level despite the aging process (4, 39). Athletes are traditionally considered as master athletes over 35 years of age, age from which the decline in endurance peak performance is engaged (4, 39). Endurance performance depends on maximal oxygen uptake ($VO_{2max}$), the ability to sustain a high percentage of $VO_{2max}$ for an extended period and the energy cost of locomotion (1, 30).

Classically, energy cost is assessed in cycling using different efficiency values (i.e. body's effectiveness in using the oxygen to produce energy and to convert it into work, during cycling) while running economy or energy cost of running are commonly used to observe if an athlete is consuming lower energy during constant speed (20). Energy cost of running is defined as the energy spent per unit distance during constant speed running (30). Therefore, in cycling a better efficiency is associated with high values of efficiency and in running with lower values of energy cost or running economy. Although the effect of age on $VO_{2max}$ has been well described in Masters with a significant decrease of ~5% per decade after age of 25–30 years (39), the effect of age on the energy cost of running is less clear, which makes its importance as a determinant factor of performance in this population questionable (1, 28, 39).

The first studies about the changes in energy cost of locomotion with aging have evaluated running economy in older athletes suggesting a similar energy cost (or running economy) when compared with younger athletes (1, 31). Contrastingly, in cycling, recent studies evaluating older well-trained triathletes and cyclists found that the cycling efficiency is reduced with aging (5, 20, 28). In these studies, it has been demonstrated that the delta efficiency (i.e. the ratio of the change in work output to the change in energy expended), which is considered as the best cycling performance indicator and a valid estimate of efficiency in cycling, is 10.7% lower in masters than in young subjects (20). Among the hypotheses raised in these studies it has been observed that cycling efficiency was highly correlated with maximal strength production (20) or maximal cycling power output (5). This suggests that the inevitable loss of muscle strength in the highly trained older athlete may partly explain the decrease in muscular efficiency.

Since the initial studies, very limited attention has been provided to the changes in endurance running energy cost with ageing and several factors should be considered since running energy cost is influenced by physiological (muscle fiber type, core temperature, ventilation, heart rate), biomechanical (ground reaction forces, storage and restitution of elastic energy, musculo-tendinous stiffness, resonant frequency) and anthropometrical factors (limb dimensions, body fat, body weight), as well as on training and environment (30, 35). A recent study comparing young and older runners has found that the older group had 2-9% lower running economy than the young, across different running speeds (3). Within the older group, however, no difference was found on running economy (subjects' age was ranging from 65 to 82 years). In this study subjects were healthy but not well-trained runners, as evidenced by both their maximal aerobic capacity (average $VO_{2max}$ of 37.3 $ml.min^{-1}.kg^{-1}$) and the running speeds investigated (2.91 $m.s^{-1}$ at most, which is quite far from the usual training and competing speed of a master runner). A speed expected for a master runner (older runner who is well trained and is competing) is commonly around 4.2 $m.s^{-1}$ (19), which is considerably higher than the speed used in the aforementioned study. Within this framework, it has been shown that well-trained master athletes have a higher energy cost of running than their well-trained younger counterparts, while no measure of biomechanical factors was reported (28). Thus, to date, very little is still known about the energetic cost of running and running mechanics in the specific context of trained master athletes.

Contrary to cycling, running is a weight-bearing activity involving a bouncing mechanism. The most classical and integrative mechanical model used to characterize running is the spring-mass model which includes stretch-shortening cycle (SSC) actions in the lower limb (21). The associated storage and return of elastic energy via tendon recoil can minimize the energy cost required for performance (7). For example, studies evaluating the effect of plyometric training (including SSC actions) in young runners showed an improvement in rate of force development and muscle-tendon stiffness associated with an increase in elastic energy return, leading to a reduction in energy cost of running (26). However, few studies evaluated storage-restitution of elastic energy in older trained endurance runners (15). One of these studies showed that the tendon stiffness of the *triceps surae* and *quadriceps femoris* muscle-tendon units was similar between older runners and their sedentary counterparts, although the *quadriceps femoris* tendon stiffness was lower in older subjects (sedentary and runner) when compared with their younger counterparts. This tends to suggest that endurance running does not counteract the age-related degeneration of the muscle-tendon units (15). Therefore, it is reasonable to hypothesize that the lower force capabilities of the lower limb observed in the older population will also lead to an altered elastic recovery and in turn an impaired energy cost of running in master runners compared to young runners. In master athletes lower limb power (as measured during jumping or running tests) may also be associated with energy cost of running (23). When analyzing running mechanics with the spring-mass model, some studies have suggested that the stiffness of the spring was associated with the energy cost of running (10, 22), although other studies found contrasting results (13, 38). In this model, vertical stiffness ($k_{vert}$) describes the vertical motion of the center of mass (CM) during contact and is defined as the ratio between the maximal vertical force and the vertical displacement of the CM as it reaches its lowest point (i.e. middle of stance phase during running). Leg stiffness $k_{leg}$ is defined as the ratio between the maximal vertical force and the maximum leg compression at the middle of the stance phase (21, 24). These parameters can be obtained using force platforms, yet this method is costly and not applicable in field conditions (24). Therefore, some recent studies have indicated the possibility to asses these parameters during running or jumping from contact and flight time measurements (11, 24). To date very few studies have evaluated spring-mass model stiffness in the older population, especially in master athletes indicating either no difference in $k_{vert}$ during running between older and younger (sedentary and runners) (7) or a lower $k_{leg}$ in older runners when compared to the younger (3).

Considering the lack of data on older, yet well-trained athletes and the conflicting results regarding energy cost of running and its underlying factors in master runners, more studies are needed to clarify the effect of aging not only on cardiorespiratory variables but also on biomechanical variables (such as lower limb stiffness and power) that have been related to energy cost of running and thus endurance performance (35). The analysis of lower limb power and spring-mass model behavior in endurance master athletes may be useful to explain the energy cost of running in this population. Therefore, the aim of this study was to compare energy cost of running at typical practice speeds between well-trained endurance master athletes and their younger counterparts, considering (i) lower limbs spring-mass characteristics during running and jumping and (ii) lower limbs maximal power during jumping, as a way to explain possible inter-group differences in the energy cost.

## METHODS

**Subjects.** The sample comprised 10 trained young long-distance runners (age = 27.3 ± 5.27 years; body mass = 66.7 ± 6.47 kg; height = 1.80 ± 0.044 m; body fat = 14.4 ± 2.54%; lower limb volume = 12.2 ± 1.20) and 10 trained master long-distance runners (age = 62.6 ± 4.84 years; body mass = 68.6 ± 8.11 kg; height = 1.74 ± 0.087 m; body fat = 19.3 ± 3.99; lower limb volume = 11.9 ± 1.50). The sample size was calculated according to the previous study by Peiffer et al. (28) investigating the effect of aging on running economy (effect size: Cohen's d = 2.8) with a statistical power of 80%. All participants were road running or triathlon competitors practicing at least three hours per week for the masters group and four hours per week for the young group and were free from any injury that could prevent them from performing the tests. The weekly running training distance was on average 68 ± 26.2 km for the younger subjects and 42.6 ± 26.0 km for the older group. After being informed about experimental procedures, which were approved by the local ethical committee and were in agreement with the Declaration of Helsinki, the athletes provided written consent for participating in the study.

**Study design.** The athletes participated in two sessions of measurements: in the first session, anthropometric data were collected and the athletes performed jump tests and an incremental test on the treadmill, after an appropriate warm up adjusted to their own training practice. The jump tests were performed to evaluate lower limb power capability and stiffness. The incremental test was used to obtain the $VO_{2max}$ and the first and second ventilatory thresholds (VT1 and VT2) allowing the calculation of 90% VT2 intensity, which was used in the energy cost of running protocol. Before the incremental test, a familiarization with the treadmill was made at the end of which the self-selected speed of each subject was recorded.

In the second session, an energy cost of running test was performed to assess this variable. The two sessions were performed with an interval of at least 72 h and no more than two weeks. Subjects were instructed to avoid strenuous exercise within the 24h preceding the tests and they were also asked to avoid consuming beverages with caffeine and eat a light meal at least two hours before the tests.

**Anthropometric measurements.** Body composition was estimated on the basis of four skinfolds thickness measured with a Harpenden caliper. Body fat percentage was estimated using Siri's (37) equation. Sub-ischial length, referred to as leg length (L, cm) was measured from the great-trochanter to the ground, while subjects were in a standing position with shoes (for leg stiffness calculation during running) and without shoes (for lower limb volume calculation). Lower limb volume was calculated based on the measurement of five circumferences, as proposed by Shephard et al. (36).

**Jump tests.** Athletes performed three types of vertical jump test to obtain lower limb power and stiffness: squat jump (SJ), countermovement (CMJ) and rebound jump (RJ) were performed in that order. Before beginning the tests and after their standardized warm-up they were familiarized with the protocol and 2 to 5 jumps were allowed for practice and correction of the technique. All jumps were evaluated with the OptoJump Next system version 1.9 (Microgate, Bolzano, Italy) allowing the measurement of contact time (CT) and flight time (FT). Two jumps of each type were performed with hands placed on the hips. If there was more than 5% difference between jump height values of the two jumps, a third jump was performed. For the SJ, subjects had their initial position checked before the execution of the jump in order to standardize the vertical push-off distance (hpo) for each subject. The CMJ was performed from a standing position and subjects were instructed to flex their knee until ~90° and perform the jump as quickly as possible. The RJ consisted of seven jumps performed as quickly as possible and subjects were asked to rebound for maximal height at each jump.

The average height for the two jumps was obtained for SJ (hSJ) and CMJ (hCMJ) and used to calculate lower limb power based on Samozino et al. (33) equation:

$$P = mg\left(\frac{h}{hpo} + 1\right)\sqrt{\frac{gh}{2}}$$

where *m* is body mass; g is the gravitational acceleration; *hpo* the vertical push-off distance; and *h* the jump height. The *hpo* variable was calculated as the difference between lower limb length in SJ initial position (from the iliac crest to the tip of the toe with the subject lying in a supine position, with feet in plantarflexion, simulating the take-off position of the SJ) and lower limb height in SJ take-off position (from the iliac crest to the ground with the subject standing in the initial position of the jump) (38).

The RJ power was calculated from CT and FT measurements using the equation proposed by Dalleau et al. (11):

$$P = \frac{mg^2}{CT}\left(\frac{FT^2}{4} + \frac{CT(CT + FT)}{\pi} - \frac{CT^2}{4}\right)$$

The lower limb power obtained for each type of jump was divided by body mass, and expressed in W.kg$^{-1}$.

Finally, stiffness during RJ was obtained using the equation proposed by Dalleau et al. (11) and expressed in kN.m$^{-1}$:

$$K = \frac{m \times \pi(FT + CT)}{CT^2\left(\frac{FT + CT}{\pi} - \frac{CT}{4}\right)}$$

**Incremental test.** After the jump test, athletes had a familiarization with the treadmill (Gymrol S2500, HEF Tecmachine, Andrezieux-Boutheon, France) for 10 min (5 min at 10 km.h$^{-1}$ and 5 min at 12 km.h$^{-1}$) and the self-selected speed was determined. For self-selected speed determination, subjects were allowed to run at different speeds on the treadmill and select the one that they felt was more comfortable, without any feedback. The speed decreased or increased in accordance with the subject's feedback to the evaluator and this test was repeated twice. Therefore, for each subject, the preferred speed was measured twice and the average value was used as the self-selected speed. One minute of rest in a standing position was needed for collection of $VO_2$, respiratory exchange ratio (RER) and heart rate (HR) to evaluate if subjects had a proper rest level to begin the test. The gas exchange measurements were made using an Oxycon Pro breath-by-breath gas analyzer (Jaeger, Hoechberg, Germany) and before the beginning of the test the device was calibrated in accordance with the manufacturer's instructions. This device provides a reliable measure of $VO_2$ from low to higher intensities (32). Four minutes of warm-up followed the rest period at a speed of 8 $km.h^{-1}$ for the master group and 10 $km.h^{-1}$ for the young group. After the warm-up, the speed increased by 1 $km.h^{-1}$ every minute until the athletes reached their $VO_{2max}$. The HR was controlled throughout the test. The exercise duration ranged between 10 and 15 min and the criteria used to define when athletes reached $VO_{2max}$ was determined according to following criteria: a plateau in $VO_{2max}$ despite an increase in running speed, a respiratory exchange ratio value of 1.15, or an HR over 90% of the predicted maximal HR. For the identification of the thresholds, end-tidal $CO_2$ ($PET_{CO2}$) and $O_2$ tensions ($PET_{O2}$) were evaluated following the method proposed by Wasserman et al. (40). The identification of the thresholds was made by two independent researchers and if necessary, a third researcher was consulted. The points identified were considered valid when the same value was obtained.

**Energy cost of running test.** The energy cost of running protocol was performed at three different speeds, in a random order, within the same session: 10 $km.h^{-1}$; self-selected speed; 90% of VT2. Before beginning the test athletes performed their standard warm-up and were familiarized with each speed. During this familiarization they ran 5 min at 10 $km.h^{-1}$ and at the self-selected speed, and 2 min at 90% VT2. Athletes were also trained to drop themselves onto the rolling treadmill belt at each pre-determined speed. After a 5-min rest period, subjects were prepared for the $VO_2$ data collection using the same procedure and device as in the first session. After one minute of rest in a standing position, two running bouts of 6 min were performed at each speed with 5-min rest intervals between each 6-min bout and each speed condition. For each run the subjects supported their body mass with their hands on the handrails until leg speed matched treadmill belt speed, after which they dropped themselves off the handrails and began running according to the protocol described by Caputo and Denadai (6).

Data were exported to a computer and processed in Excel. Energy cost was then calculated from the $VO_2$ amplitude data using the constants calculated from the

RER data of each athlete. The $VO_2$ values were divided by speed in $m.s^{-1}$ and by the athletes' body mass and multiplied by the calorie equivalents of oxygen utilisation, to obtain energy cost in $J.kg^{-1}.m^{-1}$ (30). The $VO_2$ of the respiratory muscles ($VO_{2RM}$) was also estimated using the equation proposed by Coast et al. (8).

Finally, using the OptoJump system placed on each side of the treadmill belt, step frequency, $k_{vert}$ and $k_{leg}$ were calculated during running at each speed based on contact and flight times during the third minute of the 6-min block. The latter variables were computed as proposed by Morin et al. (24), using calculations based on a sine-wave modeling of the vertical ground reaction force over time.

**Statistical analysis.** A descriptive analysis was made and data are presented as mean ± standard deviation (SD). The Shapiro-Wilk test was applied to check the normality of data. In case of normal distribution, an independent Student T test was performed to compare groups at each speed using the software Statistica version 7.1. Furthermore, a Pearson's correlation test was used to test the association between mechanical and energy cost variables. The magnitude of the differences found was assessed through the effect size (ES) Cohen's *d* coefficient (9). The interpretation of the effect size was as follows: $0.2 \leq d < 0.5$: small difference, $0.5 \leq d < 0.8$: moderate difference, $d > 0.8$: large difference. Statistical significance was set at $p < 0.05$.

## RESULTS

**Incremental test.** All the values recorded during the incremental protocol, for each group, are presented in Table 1. $VO_{2max}$ and maximal aerobic speed were significantly lower in master runners compared with young runners with a large effect size for both variables (28% and 25.1%; $p < 0.05$, respectively). However, no effect was found for the $\%VO_{2max}$ at VT1 and VT2 between groups. Significant differences were found between the absolute values of $VO_2$ at VT1 and VT2, with lower values for masters (20.5% and 24.7%; $p < 0.05$, respectively).

**TABLE 1.** Values recorded during the incremental protocol. Data are presented as mean *(SD)* for each group. Difference between groups for each variable is presented using Cohen's *d* (effect size: ES).

| | **Young** | **Masters** | **ES** |
|---|---|---|---|
| Heart Rate$_{max}$ (bpm) | 197 *(14.0)* | 170 *(13.5)** | 1.9 |
| $VO_{2max}$ ($ml.min^{-1}.kg^{-1}$) | 71.1 *(5.80)* | 51.2 *(4.81)** | 3.7 |
| $VO_2$ VT1 ($ml.min^{-1}.kg^{-1}$) | 50.7 *(4.35)* | 40.3 *(4.45)** | 2.3 |
| $VO_2$ VT2 ($ml.min^{-1}.kg^{-1}$) | 59.9 *(4.79)* | 44.9 *(4.57)** | 3.2 |
| $VT_1$ (%$VO_{2max}$) | 71.7 *(7.47)* | 78.4 *(8.52)* | 0.8 |
| $VT_2$ (%$VO_{2max}$) | 84.1 *(6.04)* | 88.2 *(6.92)* | 0.6 |
| Speed$_{max}$ ($km.h^{-1}$) | 21.1 *(1.52)* | 15.8 *(1.75)** | 3.2 |
| Speed 90%VT ($Km.h^{-1}$) | 15.0 *(1.20)* | 11.3 *(1.29)** | 2.9 |
| Self-Selected Speed ($Km.h^{-1}$) | 13.5 *(1.14)* | 11.5 *(1.85)** | 1.3 |

* Significant difference between young and master runners ($p < 0.05$)

**Jump tests.** The results for the three different vertical jump tests (SJ, CMJ and RJ), presented in Table 2, showed a significantly lower power output in masters with a large effect size for all jumps (28.0%; 30.5% and 27.9%; $p < 0.05$, respectively). RJ stiffness was also significantly lower in masters (27.8%; $p < 0.05$).

**Energy cost of running test.** The physiological and mechanical variables of the energy cost of running test are presented in Table 3. The energy cost of running for all speeds (10 $km.h^{-1}$, self-selected and 90% VT2) was greater in masters than in young runners showing a large effect size (13.0%; 10.8% and 7.7%; $p < 0.05$, respectively). $VO_{2RM}$ was significantly different only in 10 $km.h^{-1}$ (37.8%; $p < 0.05$) with greater values observed in master runners. Regarding the mechanical variables, no difference was found for CT, FT and step frequency in 10 $km.h^{-1}$ speed and $k_{vert}$ and $k_{leg}$ showed no significant difference between groups, for all running speeds. A significant correlation was found between energy cost (for 10 $km.h^{-1}$ and self-selected speed conditions) and SJ, CMJ and RJ power (10 $km.h^{-1}$: -0.71; -0.70; -0.47; self-selected speed: -0.76; -0.74; -0.58; $p < 0.05$, respectively).

**TABLE 2.** Mechanical variables recorded during the jump tests. Data are presented as mean *(SD)* for each group. Difference between groups for each variable is presented using Cohen's *d* (effect size: ES)

| | **Young** | | **Masters** | | **ES** |
|---|---|---|---|---|---|
| SJ Height (m) | 0.264 | *(0.029)* | 0.190 | *(0.051)** | 1.7 |
| SJ Power ($W.kg^{-1}$) | 21.2 | *(2.38)* | 15.3 | *(4.00)** | 1.8 |
| CMJ Height (m) | 0.300 | *(0.041)* | 0.210 | *(0.059)** | 1.8 |
| CMJ Power ($W.kg^{-1}$) | 24.2 | *(3.87)* | 16.8 | *(4.91)** | 1.7 |
| RJ Power ($W.kg^{-1}$) | 41.0 | *(7.92)* | 29.5 | *(9.10)** | 1.3 |
| RJ Stiffness ($kN.m^{-1}$) | 21.5 | *(6.08)* | 15.6 | *(5.39)** | 1.0 |

* Significant difference between young and master runners ($p < 0.05$)

**TABLE 3.** Physiological and mechanical values recorded during the energy cost of running test. Difference between groups for each variable is presented using Cohen's *d* (effect size: ES)

| **Running Speed (km.h$^{-1}$)** | **10** | | | **Self-Selected** | | | **90% VT** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Young** | **Masters** | **ES** | **Young** | **Masters** | **ES** | **Young** | **Masters** | **ES** |
| **Physiological variables** | | | | | | | | | |
| Energy cost (J.kg$^{-1}$.m$^{-1}$) | 4.22 (0.279) | 4.85 (0.317)* | 2.1 | 4.14 (0.199) | 4.64 (0.314)* | 1.9 | 4.34 (0.275) | 4.70 (0.270)* | 1.3 |
| VE (l.min$^{-1}$) | 45.0 (5.3) | 59.6 (10.5)* | 1.7 | 63.1 (11.8) | 71.5 (13.5) | 0.6 | 69.1 (10.6) | 69.2 (9.55) | 0.01 |
| VO$_{2RM}$ (ml.min$^{-1}$) | 413 (81.5) | 663 (206)* | 1.6 | 733 (239) | 911 (309) | 0.6 | 852 (226) | 851 (196) | 0.005 |
| **Mechanical variables** | | | | | | | | | |
| Contact time (s) | 0.307 (0.020) | 0.310 (0.026) | 0.1 | 0.261 (0.028) | 0.295 (0.040)* | 0.9 | 0.241 (0.030) | 0.292 (0.031)* | 1.6 |
| Flight time (s) | 0.053 (0.028) | 0.034 (0.018) | 0.8 | 0.086 (0.030) | 0.043 (0.025)* | 1.5 | 0.098 (0.036) | 0.044 (0.026)* | 1.7 |
| Step frequency (Hz) | 2.78 (0.159) | 2.91 (0.188) | 0.7 | 2.88 (0.199) | 2.96 (0.230) | 0.3 | 2.95 (0.179) | 2.98 (0.195) | 0.1 |
| $k_{leg}$ (kN.m$^{-1}$) | 7.47 (0.686) | 7.61 (1.13) | 0.1 | 7.01 (0.894) | 7.12 (1.82) | 0.07 | 7.23 (1.02) | 7.31 (1.43) | 0.06 |
| $k_{vert}$ (kN.m$^{-1}$) | 21.7 (3.33) | 24.5 (3.59) | 0.8 | 24.2 (3.21) | 25.5 (3.04) | 0.4 | 26.4 (2.39) | 25.7 (3.50) | 0.2 |

* Significant difference between young and master runners ($p < 0.05$)

## DISCUSSION

The main results of this study are: (1) energy cost of running was higher in master runners compared to their younger counterparts; (2) lower limb maximal power output was lower in masters with an overall significant negative correlation with energy cost; (3) lower limb stiffness was also lower in master runners during rebound jumps, although it did not differ in the running conditions.

The greater energy cost of running found in master athletes is in line with previous studies evaluating young and older cyclists or triathletes (5, 20). In addition, Peiffer et al. (28) studied well-trained young and master triathletes performing cycling and running tests and found a 10.8% higher energy cost of running and 11.2% lower cycling efficiency in master athletes. Another study on triathletes showed that the efficiency was significantly lower beyond 50 years and not before, with a mean 7.3% decline observed in the 50-59 years group and an 18.1% decline in the 60-69 years group when compared to the younger (< 30 years) group (5). Very recently, Beck et al. (3) found that older runners had significant 2-9% lower rates of gross metabolic power across different slow running speeds (2.01, 2.46 and 2.91 $m.s^{-1}$), although running economy was preserved when comparing subjects aged 65 to 82 years. All master athletes in our study were older than 50 years and the energy cost of running decline ranged from 7.7 to 13% depending on the running speed when compared to the young group.

Other studies found contrasting results. Allen et al. (1) compared master runners with matched younger runners based on performance and training and found no significant difference in running economy between the groups. Similarly, Quinn et al. (31) evaluated the effect of age on running economy in male and female distance runners and no significant difference was found between young (18-39 years), older (40-59 years) and much older (60 years and more) subjects. The explanation of such a discrepancy between studies is not clear, but it may be associated with the different methods used (e.g. different velocities or treadmill grades used during the running economy test) and/or different characteristics of the participants included. For instance, the greater difference in energy cost we report here, compared to what Beck et al. (3) recently found, may likely be explained by the clearly higher level of training and performance of our subjects (average speed at $VO_{2max}$ of: 21.1 and 15.8 $km.h^{-1}$ for the young and older subjects, respectively in our study).

Regarding the different speeds used in our study, we did not find significant differences between young and master runners in any of the mechanical variables analyzed at a set speed of 10 $km.h^{-1}$. Differences observed at 90% VT and self-selected speeds could be a result of running at different speeds, since master athletes ran at slower absolute speeds although they were at their most comfortable speed (self-selected speed condition) or at the same physiological intensity (90% VT2). The results for contact time, flight time and step frequency were similar to leg and vertical stiffness (center of mass dynamics), i.e. not significantly different between groups. This indicates the possibility of another factor than the running mechanics measured related to the higher energy cost observed in masters during running. It is worth noting that the $VO_{2RM}$ and the VE were significantly higher for master runners at 10 $km.h^{-1}$. Thus, the increased activity of the respiratory muscles may have influenced the energy cost when the athletes were running at the same speed. Another factor that may have influenced the higher energy cost found in master runners in our study may be the negative association with the inevitable loss of lower limb strength and power with aging (12, 17). The lower power output we found in masters compared to their younger counterparts, as well as the significant correlation between energy cost and power, support this explanation. A correlation between energy cost and hopping power was also found by Millet et al. (23) in trained young triathletes. In this study, they showed that the addition of strength training to a typical endurance training improved running economy showing the importance that neuromuscular adaptations have on energy cost of running in well-trained athletes. This result is also in agreement with the study by Piacentini et al. (29), which indicates that maximal strength training improves running economy in master endurance athletes suggesting that running economy is strength dependent in this population. It is worth noting that our participants (young and older) reported very small amounts of strength training in their regular practice (less than 1h per week on average), which further supports the natural loss of strength as an important factor increasing the energy cost of running in master athletes.

Maximal muscle power during SSC bouncing exercises like rebound jump seems to be affected by aging, with a 50% reduction between 90 and 20 years old subjects. That is an 8% decline on average per decade (12). In our study, master runners were 62.6 ± 4.84 years and their RJ power was on average 28% lower than in younger runners (27.3 ± 5.27 years). This tends to support the findings that the loss of strength is still inevitable even in master athletes, although it may be attenuated when compared to untrained older subjects especially if the master athlete is power trained (4, 17, 27). This loss of strength with aging is associated with a reduction in the cross-sectional area of type II fibers and a decline in maximal shortening velocity in type I fibers, overall leading to a lower explosive force production capability of the knee extensor muscles (17). The lower RJ stiffness found in masters is in agreement with these findings. However, $k_{leg}$ and $k_{vert}$ during running showed no difference between groups. This paradoxical finding likely reflects an adaptation process to long-lasting high-level training at submaximal running intensities, which might have preserved the running bouncing mechanism in master athletes. In addition, it is possible that master runners were not able to maintain a high level of lower limb stiffness (as requested in maximal-height RJ), whereas they were still able to produce the lower stiffness output observed during running (about twice lower value in running versus RJ conditions, Table 2 and 3). This impaired maximal rebound stiffness compared to younger subjects likely illustrates the typical decrease in explosive maximal power in masters. Indeed, strength loss with aging especially for type II fibers (which are known to be recruited during maximal SSC jumps – (16, 17)), is probably responsible for this difference in RJ stiffness and maximal power between young and master athletes (17). Since endurance running requires a comparatively less intense bouncing mechanism than maximal RJ and recruit predominantly type I fibers (21, 25), it is possible that the loss of type II fibers does not affect lower limbs stiffness in this activity. Furthermore, our results show a slightly higher step frequency in master athletes when compared to their younger counterparts which is probably associated with the shorter flight time in the older runners (7). This may be related to the stiffness results during running. When running with a higher frequency (due to a lower aerial time), subjects “fall” at each step from a lower height in the air, thus decreasing the impulse necessary to face the impact of the body on the ground.

It is important to note that the spring-mass model considers the lower limb as a multi-joint system with an overall behavior that is different (more integrative) than single muscle-tendon unit elastic behavior. The former depends on a combination of several factors such as joint stiffness, activation of specific muscle groups involved in running and their antagonists, touchdown angles, etc. (14). Although it is correctly describing running mechanics and bouncing behavior this might not reflect the specific behavior of all muscle-tendon units involved (7, 10). Beyond the macroscopic spring-mass model used, the evaluation of stiffness could be improved by the analysis of the specific behavior of muscle-tendon units and joint stiffness using a dynamometer and ultrasound images (34). However, these methods are unpractical in high-speed running conditions, whereas the spring-mass model has often been used in such conditions (7, 21, 24) and the stiffness results we found are in agreement with previous studies (2, 7). Cavagna et al. (7) compared running mechanics between young and older subjects and found a similar $k_{vert}$ between groups, although the older group showed a reduction in ground reaction force production and had an approximately 20% lower elastic energy restitution compared to young subjects. This suggests that the storage-restitution of elastic energy in the muscle-tendon unit was impaired in older subjects, while the macroscopic behavior of the overall spring-mass system analyzed by the dynamics of the center of mass ($k_{vert}$) was similar between groups. The authors also indicated that a greater amount of muscular work had thus to be done at each step which was associated with a higher energy cost. Arampatzis et al. (2) showed that economical runners were able to use more elastic energy than less economical runners, decreasing the mechanical work done by the contractile elements of the *quadriceps femoris* muscle-tendon unit. Therefore, it is possible that a lower elastic storage and restitution capability in the master athletes we tested may have also played an important role in their higher energy cost. In contrast, Dalleau et al. (10) found a significant relationship between energy cost and $k_{vert}$ during running, yet only for the propulsive leg data. The fact that we found similar $k_{vert}$ and $k_{leg}$ between groups during running, while the energy cost was different, might also reflect the dependence of running economy on many other factors than the bouncing mechanisms only. According to Saunders et al. (35), running economy depends on several factors such as ventilation, training, body composition, muscle fiber-type, ground reaction forces, muscle stiffness, and storage and restitution of elastic energy. Therefore, a long-lasting running practice might have resulted in similar spring-mass model behavior between young and master runners, yet strength loss, possible differences in muscle-tendon stiffness and the associated impairment of elastic energy storage-restitution mechanisms with aging, might have been responsible for the overall higher energy cost found in the master athletes in our study.

This study has limitations that must be acknowledged. The cross-sectional comparison design used is a limitation because participants did not have exactly the same running and training experience, especially as to the intensity of their training session at the time of the study. That said, the ideal long-term follow-up study would have been very difficult to perform. Another limitation is that we have two overall groups (young versus older athletes) and not one for each age group (per decade) to more accurately identify the effect of age on energy cost. Finally, it could have been interesting to run a complete movement analysis using force plates and motion capture along with the energy cost measurements, to allow a more detailed analysis. Nevertheless, the macroscopic method used in this study is valid, practical, and gives an overview of the main mechanisms underlying the running gait and its relationship with energy cost. In future studies, the analysis of running economy and detailed running mechanics in groups of master athletes divided per decade (up to over 80 yrs) could give further insight into the effect of age and training on these variables. In conclusion, well-trained master athletes showed higher energy cost of running than their younger counterparts and this is associated with a lower muscle power production. In addition, the bouncing mechanism in maximal jumping was impaired in older runners, however, during running it seemed to be preserved.

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## APÊNDICE A

## FICHA DE DADOS INDIVIDUAIS

**Nome:**____________________________________________________

**Data:**__________________

**Endereço:**_________________________________ **Bairro:** ______________

**Cidade:**_____________________ **CEP:** ______________

**E-mail:**_____________________ **Fone:** ______________

**Data de nascimento:**___________ **Idade:** ______________

**Massa Corporal:**__________ **Estatura:** _____________

**CMI:**_____________

**Doenças ou Lesões:**________________________________________________

_____________________________________________________________________

_________________________________________________________________

**Medicamentos:**________________________________________________________

_________________________________________________________________

___________________________________________________________________

**Quantas vezes treina por semana:**______________________

**Categoria e modalidade de competição:** ______________________________

**Quando começou a treinar a corrida de velocidade:**_______________________

**Quando começou a competir:**__________________________________________

**Observações:**_____________________________________________________

# ANEXO A
# DECLARAÇÃO SOGIPA

## DECLARAÇÃO

Vimos por meio desta, declarar que a Sociedade de Ginástica Porto Alegre, 1867- SOGIPA, apoia o projeto de doutorado intitulado "Efeitos da carga sobre a mecânica e a energética da corrida de velocidade", da doutoranda do Programa de Pós Graduação em Ciências do Movimento Humano da UFRGS, Patrícia Dias Pantoja, orientada pelo professor Dr. Leonardo Alexandre Peyré-Tartaruga, permitindo o uso da pista de atletismo para realização das coletas de dados. Estes dados servirão como base científica para avaliação do desempenho dos atletas velocistas.

Porto Alegre, 22 de julho de 2014.

José Haroldo Loureiro Gomes
Treinador Chefe de Atletismo da SOGIPA

Jorge Teixeira
Diretor Departamento de Atletismo